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STRATIGRAPHY AND SEDIMENTOLOGY OF UPPER DEVONIAN STRATA, HAY RIVER, N.W.T.

by

© MARK GREGORY HADLEY

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

DEPARTMENT OF GEOLOGY

EDMONTON, ALBERTA
FALL, 1987

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled STRATIGRAPHY AND SEDIMENTOLOGY OF UPPER DEVONIAN STRATA, HAY RIVER, N.W.T. submitted by MARK GREGORY HADLEY in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

Supervisor

Stelck

Thomson

Date Aug 5 1987

DEDICATION

To my parents; my father for his guidance and tutelage and my mother for her support and understanding.

ABSTRACT

Upper Devonian strata in the Hay River area, previously referred to the Hay River Formation, can be divided into four formations; the Waterways, Muskwa, Fort Simpson and Escarpment formations. The Fort Simpson Formation can be subdivided into four members, A to D, and the Escarpment Formation into five members, A to E. Strata of the Waterways Formation and members A to C of the Fort Simpson Formation were deposited during a transgression while strata of member D of the Fort Simpson Formation and the Escarpment Formation were deposited during a regression. These strata were deposited on low angle slopes with a ramp morphology.

Interbedded, argillaceous limestones and calcareous shales of the Waterways Formation disconformably overlie shallow water, platform limestones of the Slave Point Formation. The disconformable surface is represented by hardgrounds which formed on topographic highs on the surface of the Slave Point Formation. Black bituminous shales of the Muskwa Formation overlie the Waterways Formation and, locally, the Slave Point Formation where the Waterways Formation is absent due to nondeposition. The black shales record a period of stagnation in the basin during which time organic rich sediments were deposited under anaerobic conditions. The Muskwa Formation is overlain by a thick sequence of calcareous shale with some limestone and carbonate-siliciclastic interbeds of the Fort Simpson Formation. Members A to C of the Fort Simpson Formation were deposited in deep subtidal environments below storm wave base. A widespread hardground formed in the limestone at the top of member A during a pause in sedimentation. The strata of member D of the Fort Simpson Formation record the start of a regression during which storms reworked terrigenous quartz basinward and formed current bedded, calcareous siltstones, tempestites, hardgrounds and firmgrounds, characterized by trace fossils of the *Glossifungites* and *Trypanites* ichnofacies.

Thickly interbedded shale, fossiliferous limestone and carbonate-siliciclastics of the overlying Escarpment Formation represent a cyclic style of sedimentation. During periods of reduced clastic influx to the basin a diverse community of benthic organisms, dominated by brachiopods, corals and stromatoporoids, colonized the sea floor and locally formed extensive biostromes and bioherms. High energy, current bedded, calcareous, quartzose sandstones were deposited during periods of increased clastic influx. Cessation of terrigenous influx allowed the proliferation of organisms and the development of the shallow water reefal, lagoonal and tidal flat deposits of the Alexandra Member of the Twin Falls Formation.

Hardgrounds occur at or near the upper boundary of the Slave Point Formation, at a number of levels in the Waterways Formation, near the top and bottom of the Fort Simpson Formation and at a number of levels in the Escarpment Formation. Three types of hardgrounds occur: (1) simple hardgrounds, (2) bored hardgrounds containing *Trypanites weisei*, and (3) bored and encrusted hardgrounds. Encrusting organisms are represented mainly by *Aulopora* sp. and *Spirorbis* sp. Hiatus concretions and/or reworked hardgrounds occur in close association with the hardgrounds.

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I would like to thank my thesis committee, Dr. C. R. Stelck, Dr. B. D. E. Chatterton and Dr. S. Thomson, for helpful suggestions and constructive criticism.

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I. INTRODUCTION

A. General statement

During the past three decades the Upper Devonian basin-filling shales and carbonates of the Western Canadian Sedimentary Basin have been extensively studied. Based mainly on geophysical logs and evidence from incomplete drill cores and limited outcrop, there have been various attempts to prove the existence of clinoforms (sloping log markers) in the thick shale packages (Oliver and Cowper, 1963; Pelzer, 1966; Sheasby, 1971; Williams, 1977; Stoakes, 1980). Due to the lack of complete cores, examination of any one log marker over its entire geographic extent was impossible. Therefore, in order to characterize the lithologic composition of marker beds, samples from a number of different markers had to be assembled into an idealized log marker. Thus, many of these studies are subject to some uncertainty. Hardgrounds are developed along certain portions of these markers (Stoakes, 1980).

In the area south of Great Slave Lake thick basin-filling shales with numerous interbeds of limestone and lesser amounts of calcareous siltstone to sandstone have been assigned to the Hay River Formation (Belyea and McLaren, 1962). Although it has been the subject of numerous studies over the past 100 years, no complete studies of the sedimentology have been made and the stratigraphy of the formation is still unresolved. The term Hay River Formation is redundant and its original usage was based upon a stratigraphic miscorrelation. In addition, two distinctive formations, which have not been recognized in this area before, occur at the base of strata previously referred to the Hay River Formation. It is evident that the stratigraphy of these Upper Devonian units needs complete revision. Well developed, widespread hardgrounds occur at the upper surface of the Slave Point Formation and in the limestone and mixed carbonate-siliciclastic beds throughout the Upper Devonian basin-filling sequence.

This study is unique in that Cominco Ltd. made 42 complete diamond drill cores available for examination (Fig. 1). The cores are from the area immediately adjacent to and

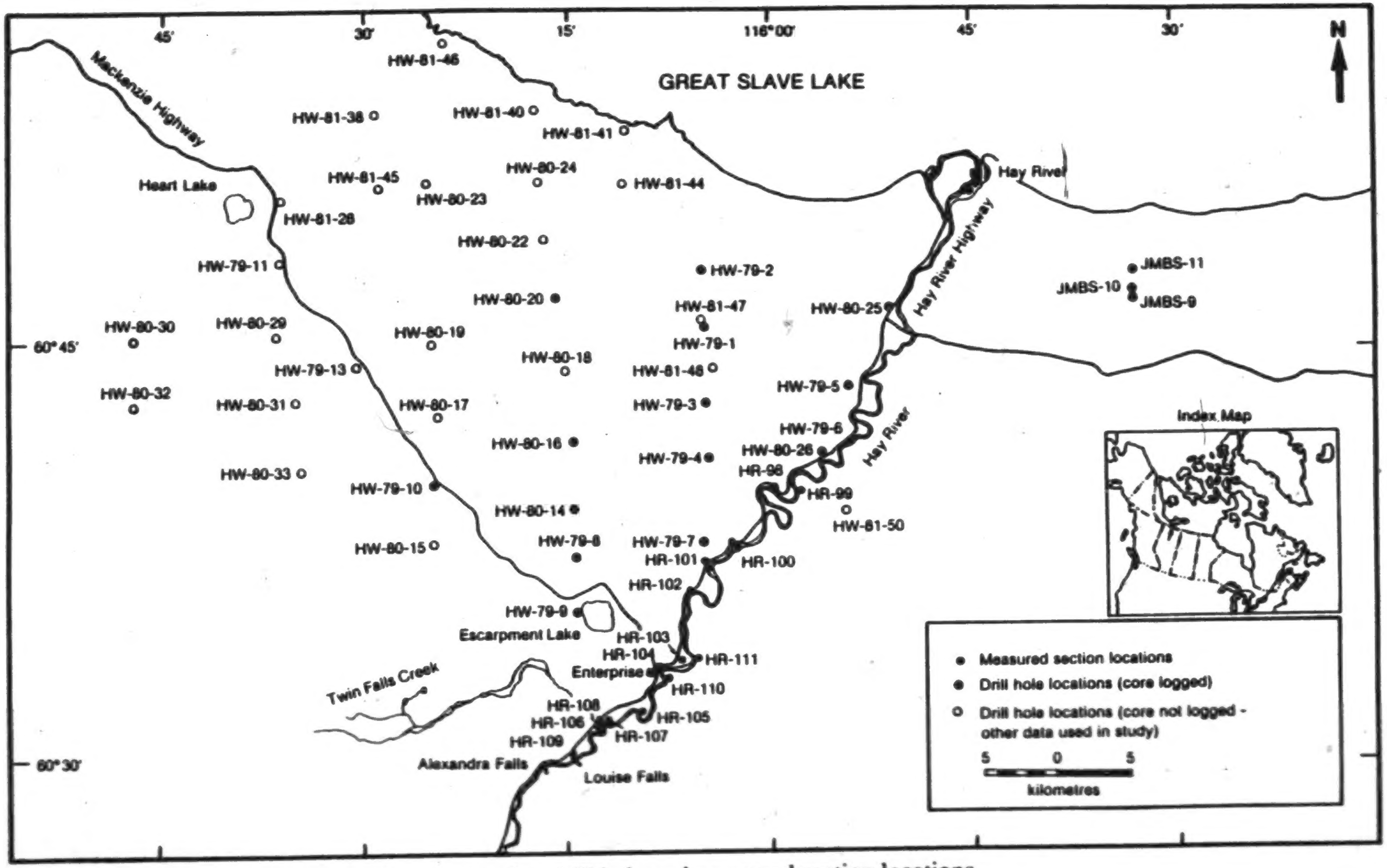


Figure 1. Location map of the study area showing drill hole and measured section locations.

surrounding the type section of strata assigned to the Hay River Formation, which, in part, outcrops along Hay River. This study provides a rare opportunity to revise the stratigraphy, determine the sedimentology of the Upper Devonian strata in this area and provide a detailed analysis of the hardgrounds in them.

B. Objectives

The objectives of this study are:

(1) to revise the stratigraphy of the Upper Devonian strata in the area around Hay River (Fig. 1),

(2) to provide a detailed analysis of the hardgrounds and related features, which occur in these strata,

(3) to provide an analysis of the sedimentology of the carbonate units and calcareous sandstone and siltstone units that occur in these strata,

(4) to establish the depositional history of Upper Devonian strata in the study area.

C. Location and method of study

The study area is located between 115° 30' and 116° 45' W longitude and 60° 25' and 60° 55' N latitude, in the southern District of Mackenzie, Northwest Territories (Figs. 1 and 2). Field work was conducted in two phases. Reconnaissance was done in the fall of 1985 when outcrops along Hay River and drill core, stored at Pine Point Mine, were examined. Some preliminary samples of the core and outcrop were taken at that time. Detailed mapping and measurement were completed in August and September, 1986. Stratigraphic sections of Upper Devonian strata, previously referred to the Hay River Formation, were described, sampled and measured at fourteen localities along Hay River (Fig. 1; Table 1). Measured sections were designated HR-98 to HR-111 to avoid confusion with those previously measured by Klapper and Lane (1985). Several sections measured by Klapper and Lane (1985) correspond to sections measured in this study (Table 1). Stratigraphically, HR-99 is the lowest section and HR-108 the highest section measured along the river. A small outboard-boat and a canoe were used to trace out distinctive beds in outcrop along the river.

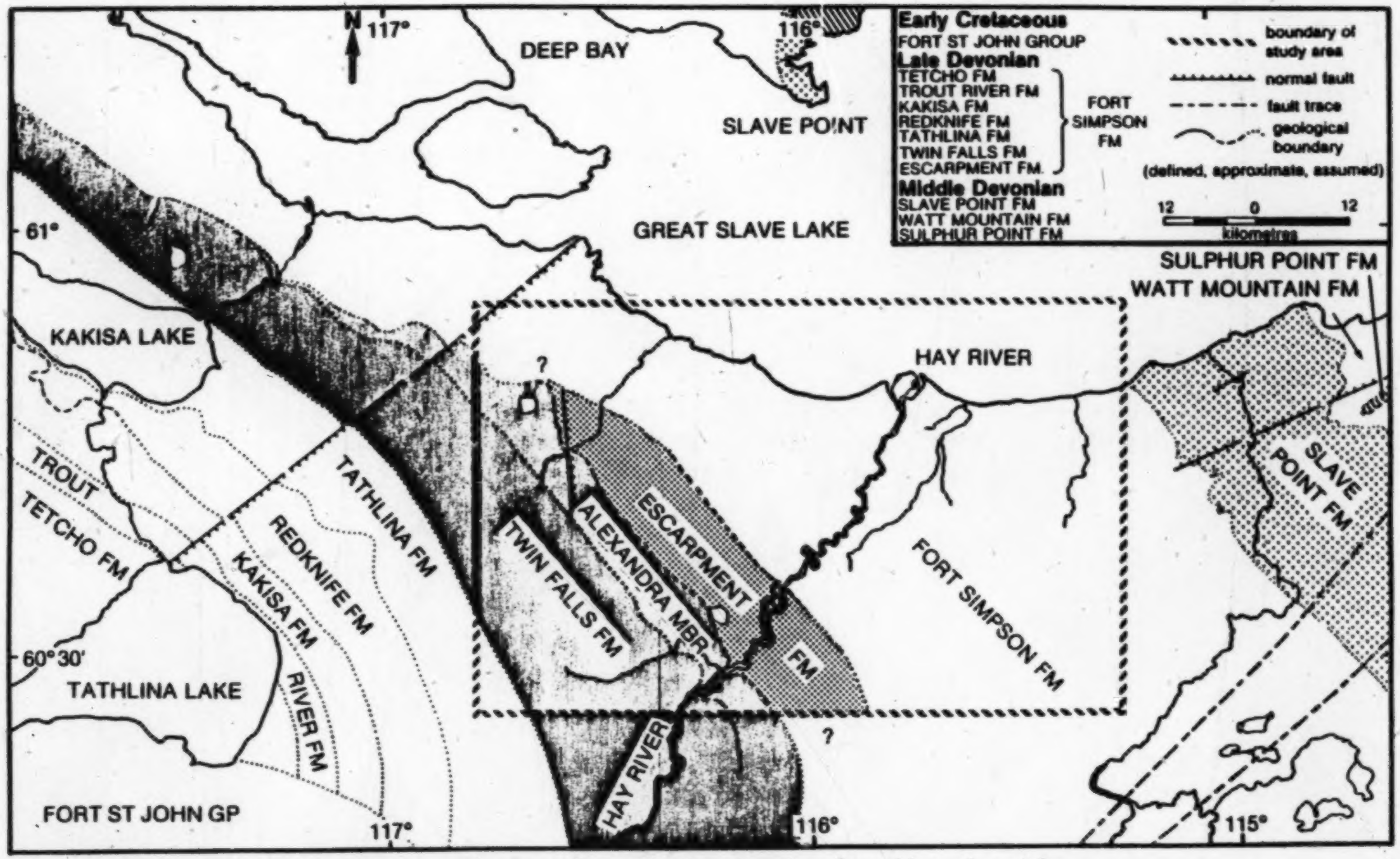


Figure 2. Geology map of the study area and surrounding region based on data from this study and from geology maps by Douglas (1974), Douglas and Norris (1974) and Rhodes *et al.* (1984).

LOCATION OF MEASURED SECTIONS ALONG HAY RIVER

Measured sections this study-1986	Location[1] (Latitude Longitude)	Measured sections - Klapper and Lane (1985)	Location[2] (Latitude Longitude)
HR-109	Lat. 60° 30' 16" N Long. 116° 15' 56" W	HR-22	Lat. 60° 30' 16" N Long. 116° 15' 56" W
HR-108	Lat. 60° 31' 28" N Long. 116° 12' 47" W	HR-16	Lat. 60° 31' 28" N Long. [illegible]6° 12' 47" W
HR-106	Lat. 60° 31' 29" N Long. 116° 12' 30" W	HR-15	Lat. 60° 31' 29" N Long. 116° 12' 30" W
HR-107	Lat. 60° 31' 32" N Long. 116° 12' 02" W		
HR-105	Lat. 61° 31' 53" N Long. 116° 09' 35" W	HR-14	Lat. 60° 31' 37" N Long. 116° 09' 10" W
HR-110	Lat. 60° 33' 09" N Long. 116° 07' 45" W	HR-12	Lat. 60° 33' 06" N Long. 116° 07' 47" W
HR-104	Lat. 60° 33' 15" N Long. 116° 06' 23" W	HR-13	Lat. 60° 33' 15" N Long. 116° 06' 23" W
HR-103	Lat. 60° 33' 40" N Long. 116° 06' 08" W	HR-11	Lat. 60° 33' 31" Long. 116° 06' 23" W
HR-111	Lat. 60° 43' 47" N Long. 116° 05' 26" W		
HR-102	Lat. 60° 36' 12" N Long. 116° 06' 05" W	HR-17	Lat. 60° 37' 10" N Long. 116° 06' 07" W
HR-101	Lat. 60° 37' 10" N Long. 116° 04' 43" W	HR-10	Lat. 60° 37' 10" N Long. 116° 04' 43" W
HR-100	Lat. 60° 37' 56" N Long. 116° 02' 31" W	HR-9	Lat. 60° 38' 06" N Long. 116° 01' 57" W
HR-98	Lat. 60° 39' 56" N Long. 115° 59' 39" W		
HR-99	Lat. 60° 39' 44" N Long. 115° 58' 03" W	HR-3	Lat. 60° 39' 44" N Long. 115° 58' 03" W

(1) locations from 1:50,000 Escarpment Lake, Sheet 85 C/9, Ed. 1 and Sandy River, Sheet 85 B/12, Ed. 1.

(2) locations from 1:250,000 Tathlina Lake, Sheet 85 C, 2nd Ed. and Buffalo Lake, Sheet 85 B, 2nd Ed.

Table 1. Comparison of sections measured during this study to those measured by Klapper and Lane (1985).

A total of 3,630 m of diamond drill core from eighteen drill holes was described, sampled and measured (Fig. 1; Table 2). Drill cores were selected on: (1) proximity to the type section of the Hay River Formation in outcrop, (2) completeness of core, and (3) preservation of core. Emphasis was placed on sampling carbonate and calcareous siliciclastic beds in the Upper Devonian shales in the study area. In every core, measurement, sampling and description was carried into the underlying Middle Devonian Slave Point Formation to: (1) determine the nature of the contact,and (2) allow the use of the top of the Slave Point Formation as a possible datum. In cores that penetrated it, the Twin Falls Formation was sampled and measured. Geophysical wire-line logs, provided by Cominco Ltd., were available for some of the holes examined (Table 2).

Approximately four hundred core and two hundred outcrop samples were collected. Samples were cut, polished, stained and laquered for visual examination with a binocular microscope. One hundred and thirteen thin sections were prepared for microscopic examination. Thin sections were impregnated with blue epoxy to facilitate the identification of original pore space. Alizarin red solution and potassium ferricyanide stain were applied, to both thin sections and slabs, to allow identification of calcite, dolomite, ferroan calcite and dolomite, respectively. Stains were applied according to the procedures outlined by Dickson (1965). Thirty two of the thin sections (of hardgrounds) were examined by cathodoluminescence using a Technosyn Cold Cathode Luminescence Model 8200 Mark II.

D. Tectonic setting

The strata in the study area are generally undeformed. However, a number of normal faults cut these strata in the surrounding area (Fig. 2). A series of northeast trending basement fault traces (Fig. 2), roughly paralleling the Hay River, have been inferred from aeromagnetic data (Norris, 1965; Belyea, 1971; Hoffman *et al.*., 1974; Rhodes *et al.* ,1984). These traces may be related to the East Arm Fold Belt and the Athapuscow Aulacogen in the Churchill Province of the Canadian Shield (Hoffman *et al.*, 1974). The influence of these faults on the deposition of Devonian strata in the area is unknown. It has been suggested, however, that they may have

Drill hole	Location (Latitude; Longitude)	Core logged	Geophysical logs	Other data used in study
JMBS-9	60° 46' 35" N; 115° 32' 30" W *	Yes		
JMBS-10	60° 47' 42" N; 115° 32' 30" W *	Yes		
JMBS-11	60° 48' 20" N; 115° 32' 30" W *	Yes		
HW-79-1	60° 46' 40" N; 116° 04' 33" W	Yes		
HW-79-2	60° 47' 40" N; 116° 04' 32" W	Yes		
HW-79-3	60° 43' 35" N; 116° 04' 30" W	Yes		
HW-79-4	60° 41' 50" N; 116° 04' 15" W	Yes		
HW-79-5	60° 44' 32" N; 116° 53' 40" W	Yes		
HW-79-6	60° 42' 00" N; 115° 53' 42" W *	Yes		
HW-79-7	60° 37' 58" N; 116° 04' 30" W	Yes		
HW-79-8	60° 37' 26" N; 116° 13' 58" W	Yes		
HW-79-9	60° 35' 30" N; 116° 14' 35" W	Yes		
HW-79-10	60° 40' 00" N; 116° 24' 30" W	Yes		
HW-79-11	60° 48' 00" N; 116° 36' 25" W			Yes
HW-79-13	60° 44' 15" N; 116° 24' 36" W			Yes
HW-80-14	60° 39' 05" N; 116° 14' 25" W	Yes		
HW-80-15	60° 38' 00" N; 116° 24' 40" W		Yes	Yes
HW-80-16	60° 41' 30" N; 116° 14' 27" W	Yes	Yes	
HW-80-17	60° 42' 26" N; 116° 24' 15" W			Yes
HW-80-18	60° 43' 57" N; 116° 14' 48" W		Yes	Yes
HW-80-19	60° 45' 05" N; 116° 25' 00" W			Yes
HW-80-20	60° 46' 54" N; 116° 15' 36" W	Yes	Yes	
HW-80-22	60° 49' 05" N; 116° 16' 35" W			Yes
HW-80-23	60° 50' 50" N; 116° 25' 26" W			Yes
HW-80-24	60° 51' 10" N; 116° 17' 00" W			Yes
HW-80-25	60° 46' 40" N; 115° 55' 03" W *			Yes
HW-80-26	60° 41' 36" N; 115° 56' 02" W *			Yes
HW-80-29	60° 45' 20" N; 116° 36' 23" W			Yes
HW-80-30	60° 45' 10" N; 116° 47' 02" W			Yes
HW-80-31	60° 43' 00" N; 116° 34' 45" W			Yes
HW-80-32	60° 42' 50" N; 116° 47' 02" W			Yes
HW-80-33	60° 40' 35" N; 116° 33' 57" W		Yes	Yes
HW-81-28	60° 50' 20" N; 116° 35' 55" W			Yes
HW-81-38	60° 53' 13" N; 116° 29' 10" W		Yes	Yes
HW-81-40	60° 53' 16" N; 116° 17' 20" W			Yes
HW-81-41	60° 52' 30" N; 116° 10' 40" W			Yes
HW-81-44	60° 50' 45" N; 116° 10' 50" W			Yes
HW-81-45	60° 50' 50" N; 116° 28' 55" W		Yes	Yes
HW-81-46	60° 56' 10" N; 116° 24' 00" W			Yes
HW-81-47	60° 45' 50" N; 116° 04' 36" W			Yes
HW-81-48	60° 43' 56" N; 116° 03' 55" W			Yes
HW-81-50	60° 39' 20" N; 115° 54' 25" W *			Yes

All Locations from 1:250,000 Tathlina Lake, Sheet 85 C, 2nd Ed. except those marked by * which are from 1:250,000 Buffalo Lake, Sheet 85 B, 2nd Ed.

Table 2. Listing of drill hole locations and type of data used in study.

had a subtle effect on the development of the trend of the Middle Devonian barrier reef complex which extends, in the subsurface, along the southern shore of Great Slave Lake into northeastern British Columbia (Bassett and Stout, 1968; Hemphill *et al.*,1970; Hriskevitch, 1970; Rhodes *et al.*, 1984). This barrier complex underlies the Upper Devonian basin-filling strata in the study area.

The Tathlina Uplift is a pre-Devonian topographic feature located west of the study area. Belyea (1971) suggested that movement of the uplift during the Early Paleozoic may have been controlled by northeast and northwest trending lineaments linked to the East Arm Fault Zone. During Middle Devonian time the uplift existed as an arcuate upland in a widespread inland basin. Periodic uplift may have affected deposition during this time. Belyea (1971) suggested that the Middle Devonian Slave Point Formation was deposited during a time of stable marine conditions. This was followed by uplift and erosion after the Slave Point Formation was deposited. Succeeding Upper Devonian shales thin toward the apex of the Tathlina Uplift (Belyea, 1971; Williams, 1977). It has not been determined whether or not the thinning of these units was due to tectonic activity of the uplift during Late Devonian time.

E. Rock classification - terminology

Introduction

The strata in the study area are lithologically diverse. The rocks consist of three major groups, shales, carbonates, and mixed siliciclastic-carbonate rocks. The term shale is used herein to define a group of fissile to laminated, clay rich, variably silty and calcareous rocks. The term is used in a broad sense following Ingram (1953), Folk (1968) and Pettijohn (1975). Recently, Lundegard and Samuels (1980) suggested that the term shale should be used in a restricted sense for a type of mudrock displaying fissility and lamination. The term mudrock is herein used for variably calcareous, nonfissile, blocky, indurated, clay rich rocks. This term is used instead of terms such as mudstone which may be confused with the term mudstone in Dunham's (1962) classification of carbonate rocks. Mudrocks are rare in the strata of the study area and for the purposes of this study have been included with the shales.

Carbonates and mixed siliciclastic-carbonates in the study area are variable in composition. Numerous classification schemes have been proposed for mixed siliciclastic-carbonate rocks (e.g. Zuffa, 1980; Mount, 1985). However, for the purposes of this study these proved to be too complex and unwieldy. Therefore, a simple twofold classification system was applied to the rocks. The first was a compositional classification (Fig. 3) based on the relative percentages of three end members (quartz, calcite and dolomite) irrespective of their distribution in the rock. The second classification applied to the rocks was a textural classification scheme. Mixed siliciclastic and carbonate rocks were classified according to the Wentworth Grade Scale (Wentworth, 1922), and roundness classifications of Powers (1953). Limestones and quartzose limestones were classified according to Embry and Klovan's (1971) modified version of Dunham's (1962) limestone classification. Estimates of the percentages of grains and carbonate allochems were aided by the visual estimate charts in Flügel (1982).

Accessory minerals, as defined herein, refers to any mineral that comprises less than 10% of the rock. These include pyrite, glauconite, feldspar, muscovite and/or sericite and in some cases may include the end members, quartz, calcite and dolomite. Bedding terminology was based on the scale of stratification thickness of Blatt *et al.* (1980, p. 128). Commonly, strata in the study area are bioturbated. In these cases, the degree of bioturbation was classified according to Frey and Pemberton (1985).

Compositional classification

Most of the carbonate and mixed siliciclastic-carbonate rocks in the study area consist of limestones, quartzose limestones, and calcareous sandstones to siltstones; locally, dolomitic varieties occur. The siliciclastic rocks consist mainly of detrital quartz with rare microcline, muscovite and/or sericite. In all of the samples examined, the size of the quartz was relatively uniform, ranging from very coarse silt to very fine sand size. Carbonates in the study area are commonly argillaceous. In these cases, the modifying term argillaceous is qualitatively applied to the rocks where they contain shaley seams or stringers or are rubbly or recessive weathering in the field or in core.

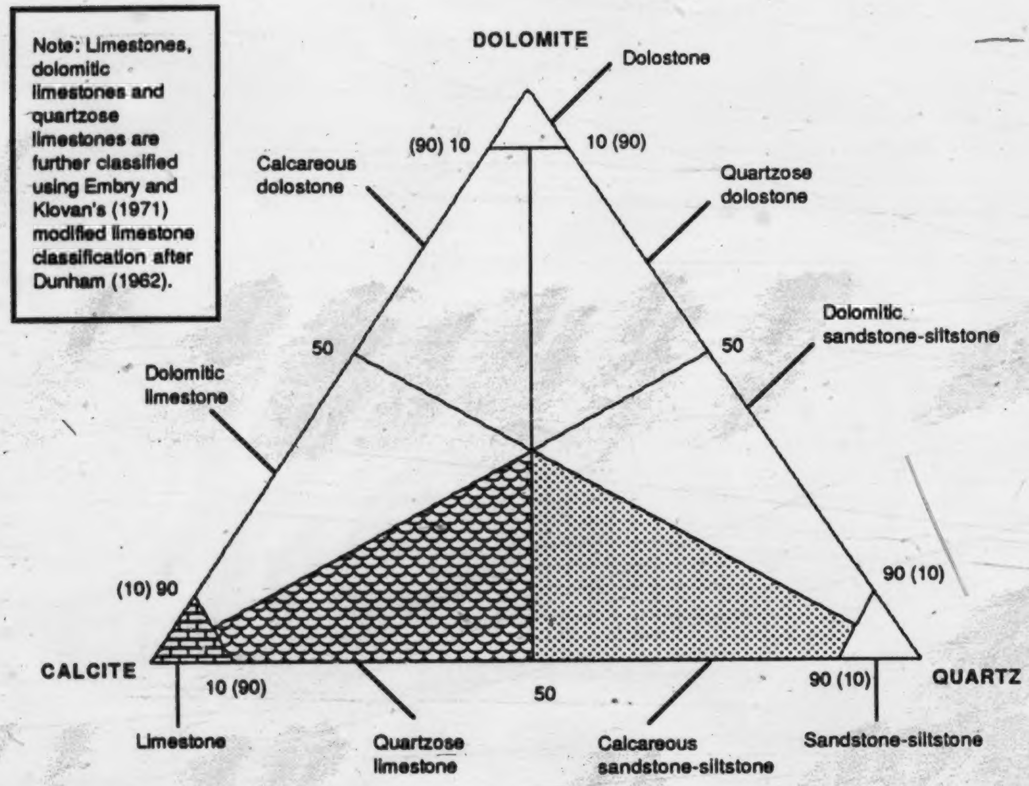

Note: Limestones, dolomitic limestones and quartzose limestones are further classified using Embry and Klovan's (1971) modified limestone classification after Dunham (1962).

Figure 3. Compositional classification of lithology types. Note that the dominant lithologies which occur in the study area are shaded.

Carbonate rock types

Carbonate rocks in the study area are lithologically diverse and range from featureless mudstones to bindstones. The classification scheme of Embry and Klovan (1971) was applied to these rocks. The basic descriptive terms of the classification were modified by using the dominant allochem(s) in the rock as a prefix. A wide variety of allochems occur, including skeletal material, coated grains, intraclasts, black pebbles and peloids. Most of the allochems consist of skeletal material. Where skeletal material accounts for greater than 10% of the rock, the modifier fossiliferous was applied.

Coated grains are represented by ooids and oncoids. The term ooid is used herein, *sensu* Teichert (1970), for a discrete particle as distinct from the rock (oolite). As noted by Richter (1983) ooids and oncoids differ mainly by a regular and irregular layering of the cortex, respectively.

Peloids are locally abundant in the carbonates, commonly occurring in shelter structures, as sediment floors in cavities and associated with burrows and borings. The term peloid is herein used to define an ovoid particle of aphanitic limestone (McKee and Gutschick, 1969). No genetic connotation is implied in this definition.

Black pebbles are common in many of the carbonate and mixed carbonate-siliciclastic beds. The term black pebble is herein used for any limestone particle greater than 1.0 mm long which is black, dark grey or has a dark rim. No genetic connotation is implied because the pebbles may be attributed to more than one origin. Most of the pebbles are probably hiatus concretions while others are of dubious origin.

The terms, micrite, microspar and spar calcite are used here following the definition of Folk (1959, 1962, 1965). Unlike Folk, however, these terms are herein used with no genetic connotations. Dolomite textures were classified according to the scheme proposed by Gregg and Sibley (1984).

Many of the carbonate units in the upper part of the Upper Devonian sequence are richly fossiliferous and exhibit a biostromal and rarely a biohermal morphology. The term biostrome is herein used for a laterally extensive, bedded, blanket-like carbonate composed mainly of the skeletal remains of *in situ* organisms (Cummings, 1932; Heckel, 1974; James, 1987). The term biohermal implies a lens, dome, or mound shaped carbonate buildup composed mainly of the skeletal remains of *in situ* organisms (Cummings, 1932; Heckel, 1974; James, 1987). The term reef or "reefal" is herein used to denote a massive or layered, laterally restricted carbonate buildup which formed *in situ*, possessed topographic relief, was potentially wave resistant and was stabilized syndepositionally by organic growth and/or submarine cements (James, 1987).

II. STRATIGRAPHIC SETTING AND HISTORY OF INVESTIGATION

A. Introduction

The Upper Devonian (Frasnian) basin-filling shales and carbonates in the study area are underlain by platform carbonates of the Middle Devonian (Givetian) Slave Point Formation and overlain by carbonates of the Upper Devonian (Frasnian) Twin Falls Formation. In the study area, these strata dip very gently to the southwest. Progressively younger strata are exposed to the west of the study area (Fig. 2). The regional stratigraphy of the Middle to Upper Devonian is complex. Within the Upper Devonian, in and around the study area, a number of formations have been recognized. The boundaries between these units are commonly vague and confusion is created by a plethora of names and a lack of paleontological age control.

B. Slave Point Formation

The term "Slave Point limestones" was introduced by Cameron (1918, 1922) for 61 m (200 ft) of grey brown, thinly bedded, fossiliferous and bituminous limestone with some beds of calcareous shale, that are exposed along the north and south shores of the west arm of Great Slave Lake. Campbell (1950) raised the "Slave Point limestones" to formational status and informally divided the formation into a lower argillaceous, fossiliferous limestone unit, a middle fragmental limestone unit and an upper stromatoporoidal unit. In addition, he recognized a distinctive 3 m (11 ft) thick unit, occurring 9 m (30 ft) above the base of the formation, which he referred to as the "Amco shale".

Law (1955) studied the Slave Point Formation in the subsurface of northern Alberta, designating the section between 1301.5 m (4270 ft) and 1357 m (4452 ft) in the California Standard Steen River No. 1 well (2-22-117-5W6) as a reference section for the formation. Law (1955) divided the Slave Point Formation into a lower, Fort Vermilion Member and an upper, unnamed member. He suggested that the term Slave Point Formation should apply only to the carbonates between the "Amco shale" and the overlying Upper Devonian shales.

The Slave Point Formation is represented by a sequence of tidal flat to shallow platform carbonates (Rhodes *et al.*., 1984). The Amco shale is recognizable in the Pine Point region and is considered to represent a time stratigraphic marker at the base of the Slave Point Formation (Rhodes *et al.*, 1984). The various subdivisions and facies relationships of the Slave Point Formation in this area have been discussed in detail by Richmond (1965), Skall (1975) and Rhodes *et al.* (1984). Present nomenclature at the Pine Point Mine continues to follow Skall's fourfold subdivision with only minor changes in lithological descriptions (Rhodes *et al.*, 1984).

In northeastern British Columbia and northwestern Alberta the Slave Point Formation is unconformably overlain by black bituminous shales of the Muskwa Formation (Gray and Kassube, 1963; Griffin, 1965, 1968; Hriskevitch, 1970; Torrie, 1972) and the Waterways Formation. In northeastern Alberta the Slave Point Formation is locally overlain by the Peace Point Member of the Waterways Formation (Norris and Uyeno, 1981, 1983; Park, 1984).

The Slave Point Formation contains a sparse, poorly preserved, low diversity megafauna that occurs in a post-*Stringocephlus* stratigraphic position (Norris and Uyeno, 1983). Belyea and Norris (1962), House and Pedder (1963), Loranger (1965), McGill (1966), Braun (1968), Crawford (1972), Featherstone (1982) and Johnson *et al.* (1985) all suggested a Late Givetian age for the Slave Point Formation. However, some workers have argued that the age of the upper part of the Slave Point Formation may be regionally variable (Crawford, 1972; Braun and Mathison, 1982, 1986).

de Wit *et al.* (1973) noted that paleontological evidence indicated a latest Middle or early Late Devonian age for the Slave Point Formation, but suggested that this was subject to interpretation. They proposed, however, that conodonts indicated a possible Late Devonian age. Norris and Uyeno (1981) argued that the Slave Point Formation, exposed at Gypsum Cliffs in northeastern Alberta, is early Late Devonian (Frasnian) in age. This was based upon a sparse megafauna and conodont fauna and the assumption that the Middle/Upper Devonian boundary will be defined, by the Subcommission on Devonian Stratigraphy (see Zeigler and

Klapper, 1985), on the basis of the entry of *Polygnathus disparilis* at the base of the Upper Devonian.

C. Waterways Formation

The Waterways Formation was named by Warren (1933) for a sequence of limestones and shale, exposed on Athabasca River, near McMurray, in northeastern Alberta. He suggested a Late Devonian age for the formation and correlated it with the Devonian beds exposed along the Peace River at Peace Point in northeastern Alberta, and the "Simpson shales" exposed near Fort Simpson along the Mackenzie River in the southern District of Mackenzie.

Crickmay (1957) divided the Waterways Formation, in the Bear Biltmore No. 1 well (7-11-87-17-W4M) near Fort McMurray, into the Firebag, Calmut, Christina, Moberly and Mildred Members. Carrigy (1959) suggested that the term "Waterways" should not be used as a rock stratigraphic term because the definition proposed by Warren (1933) was based primarily on the presence of a characteristic fauna. The term Calmut was changed to Calumet by Norris (1963). The Waterways Formation forms the uppermost part of the Beaverhill Lake Group (Leavitt and Fischbuch, 1968). Norris (1963) designated the section in the Bear Biltmore No. 1 well, described by Crickmay (1957) as the reference section of the Waterways Formation, with the type section as defined by Warren (1933) on the Athabasca River.

An additional unit, referred to the Peace Point Member of the Waterways Formation, is locally developed in the Peace Point area of northern Alberta. The name was introduced by Norris (1963) for the lower part of the Waterways Formation, exposed at Gypsum Cliffs on the Peace River. Norris and Uyeno (1983) suggested that the Peace Point Member at Gypsum Cliffs is equivalent to the lower part of the Firebag Member as developed in the Clearwater-Athabasca Rivers area. The predominant lithology of the Peace Point Member is light to dark, variably calcareous shale with thin beds of rubbly, argillaceous, brachiopodal limestone (Norris, 1963). Lithologies from this member are commonly preserved in sink holes, widened joint fissures and other irregular cavities in the underlying Slave Point

Formation (Norris and Uyeno, 1983). The maximum thickness of exposures of the Peace Point Formation is 6 m.

In the reference section of the Waterways Formation, the Firebag Member disconformably overlies the Slave Point Formation and is conformably overlain by the Calumet Member of the Waterways Formation (Crickmay, 1957). The Firebag Member consists of 52 m (170 ft) of shale and argillaceous limestone. The overlying Calumet Member consists of 31 m (102 ft) of resistant, fine grained, clastic limestone (Crickmay, 1957). It is sharply overlain by the Christina Member which consists of 27 m (90 ft) of argillaceous limestone and shale that is overlain conformably by the Moberly Member. In outcrop the Christina Member consists of greenish grey shale, grey, argillaceous limestone and minor pale brown, fragmental limestone (Norris, 1963). Locally sandstone and sandy limestone beds are present. Norris (1973) interpreted these beds to represent a local uplift of Precambrian strata in the nearby area during deposition of the Christina Member. Crickmay (1957) introduced the term Moberly Member for the 61 m (200 ft) of predominantly clastic limestone lying between the Christina Member below and the Mildred Member above. Norris (1963) described the beds of the Moberly Member as comprising alternating sequences of light green, thinly bedded, rubbly, argillaceous limestones and shale, and even bedded, pale brown fragmental limestone. Crickmay (1957) proposed the term Mildred Member for the 43 m (104 ft) of argillaceous limestone and shale between the the Moberly Member below and fragmental limestones above.

D. Muskwa Formation

The term Muskwa Member was named by Gray and Kassube (1963) for a black, radioactive shale unit located in the upper part of strata previously referred to the Horn River Formation. Since then, this distinctive unit has been the subject of much controversy, and frequent changes to its stratigraphic rank.

The name "Horn River shale" was proposed by Whittaker (1922) for shales outcropping discontinuously along Horn River. Locally, the shales are overlain by thin limestone beds which he referred to the Pine Point Formation.

Hunt (1954) assigned the name "Spence River shale" to 47.5 m (156 ft) of bituminous, dark brown to black, calcareous to noncalcareous shale in the West Territories Westerol 7A well (61° 39' N, 120° 43' W). Although this unit was believed to correlate with Whittaker's (1922) Horn River shale, the new name was introduced because there was some question that the Horn River shales were of Cretaceous age. The term Spence River Formation has not gained wide acceptance.

Douglas and Norris (1960) assigned both the shale and limestone beds, examined by Whittaker, to the Horn River Formation. They redefined the formation to apply to a unit consisting mainly of dark shales, variably interbedded with limestones, overlying limestone of the Lonely Bay Formation and overlain by green shales of the Fort Simpson or Hay River formations or, near Horn Plateau, by reefal limestones.

The Horn Plateau Formation was named by Norris (1965) for fossiliferous, reefal limestone exposed on the east flank of Horn Plateau near Fawn Lake. He suggested that the Horn Plateau Formation unconformably overlies the Horn River Formation and is overlain unconformably by the Fort Simpson Formation. Vopni and Lerbekmo (1972) argued that reefs of the Horn Plateau Formation developed on, or within, the Lonely Bay Formation and are conformably overlain by shales of the Horn River Formation. They suggested that the Horn River and Horn Plateau formations are overlain, possibly unconformably, by the Hay River Formation.

Belyea and Norris (1962) noted that in the subsurface the contact between the shales of the Horn River and Fort Simpson formations is arbitrarily placed at a strong gamma-ray "kick" on geophysical logs, corresponding to a colour change from dark grey to green grey. In places a dark shale is present above the "kick". This unit was placed tentatively in the Fort Simpson Formation by Belyea and Norris (1962). Belyea and McLaren (1962, Fig. 3) also noted the presence of a black shale unit at the base of strata referred to the Hay River Formation. They termed this unit the "black shale member"; however, its usage was not defined.

Gray and Kassube (1963) subdivided the Horn River Formation, in the subsurface of northeastern British Columbia, into three members; the Evie, Otter Park and Muskwa Members. They designated the Western Natural *et al.* Fort Nelson a-95-J well (centizone 95, block J, NTS map sheet 94-J-10) as the type section of the formation. In the type section the Horn River Formation is 231.6 m (760 ft) thick and consists of a lower, 30.5 m (100 ft) of black bituminous shale and limestone (Evie Member), a middle, 164.6 m (540 ft) of dark grey calcareous shale (Otter Park Member), and an upper, 36.6 m (120 ft) of black bituminous shale (Muskwa Member).

Griffin (1965) separated the Muskwa Member from the Horn River Formation and raised it to formational status because of its distinctive lithology and stratigraphic relations. He noted that, in northeastern British Columbia and northwestern Alberta, the Muskwa Formation consists mainly of grey black and pyritic shales, which are locally siliceous. In most areas the formation is 15.2 m (50 ft) to 30.5 m (100 ft) thick. Locally, however, it is 45.7 m (150 ft) to 76.2 m (250 ft) thick. To the northeast the Muskwa Formation grades vertically and laterally into the Fort Simpson Formation and to the northwest into the Besa River Formation.

Griffin (1965) noted that the Slave Point Formation is overlain by strata of the Beaverhill Lake Formation (=Waterways Formation) and that the Muskwa Formation unconformably overlies both the Slave Point and Beaverhill Lake formations in northeastern British Columbia and northwestern Alberta. These strata are approximately 213 m (700 ft) thick in eastern Alberta but thin to a zero edge over the Slave Point Formation in northeastern British Columbia. Based on stratigraphic evidence Griffin (1965) suggested that the thickest section of the Slave Point Formation in this area is the facies equivalent to the Firebag and Calmut (=Calumet) Members, and at least the lower part of the Christina Member of the Beaverhill Lake Formation.

Bassett and Stout (1968) argued that the northwestward thinning of the Waterways Formation was due to onlap of these strata onto eroded limestones of the Slave Point Formation. They referred to the black, radioactive, euxinic shales, overlying the Slave Point

Formation, as the Canol Formation and suggested that the shales may have been deposited in a widespread, shallow, stagnant sea after a sudden transgression covered the entire region.

Griffin (1965) suggested that the upper part of the Otter Park Member of the Horn River Formation is equivalent to the lower part of the Beaverhill Lake Formation (=Waterways Formation). He suggested that confusion could be avoided by naming the calcareous shales to the west of the carbonate-shale facies front, the Otter Park Member and the shales to the east of the front, the Beaverhill Lake Formation (=Waterways Formation).

In the subsurface, south of Great Slave Lake, Richmond (1965) recorded 9 to 18 m (30 to 60 ft) of interbedded grey to dark brown bituminous shale and grey green calcareous shale and argillaceous limestone between the Slave Point Formation and the Hay River Formation which he assigned to the Horn River Formation. He considered it to be an upper transgressive unit of the Horn River Formation, as developed farther to the west, at the margin of the Keg River-Slave Point formations carbonate barrier complex. Similarly, de Wit *et al.* (1973; Table 4, Fig. 9) suggested that the Slave Point Formation in this area is overlain by Horn River-Muskwa formation lithologies, which in turn are overlain by green grey shales of the Fort Simpson and Hay River formations.

Williams (1977) suggested, on the basis of well log correlations, that clinoforms in the Hay River Formation slope westward. He proposed that the "toes" of the clinoforms become radioactive, black shale layers which merge to form the Muskwa Formation. He suggested that this was evidence against an erosional unconformity at the base of the Muskwa Formation. He proposed that the black shales were a starved basin, relatively deep water deposit equivalent to most of the Hay River Formation. Williams (1977, p. 11) suggested that "... the basal part of the Hay River Formation (Waterways Member), as well as the partly equivalent Muskwa Formation merge northward into the upper part of the Horn River Formation." He placed the boundary between the Fort Simpson Formation and the Horn River Formation at the top of the highest regionally mappable radioactive shale and considered this contact to be diachronous.

Williams (1983) noted that the term "Horn River Formation" now applies to two distinct rock units of different ages: (1) Type A, a thick but narrow wedge of calcareous shale and carbonate abutting the seaward edge of the Keg River Formation-Slave Point Formation carbonate barrier complex, which is mainly Givetian in age, and (2) Type B, a thin but widespread unit of dark, radioactive shale that is largely of Frasnian age. For mapping purposes he considered these dissimilar units to be homotaxial and, therefore, one and the same unit.

A number of workers (Bassett and Stout, 1968; Tassonyi, 1969; Pugh, 1983) have recognized that the use of the term Horn River Formation can be extended to units occurring northward from the southern District of Mackenzie. However, a wider adoption of the term, as Pugh (1983) pointed out, has been inhibited by an uncertain belief in a regional unconformity below the Canol and Muskwa formations. Based on a study of measured sections in the Richardson Mountains and in the subsurface, Pugh (1983) concluded that there was no evidence of truncation of Lower and Middle Devonian beds below the Canol Formation. This conclusion challenges the concept of an Upper Devonian unconformity in western Canada, at least, in the deep basinal strata of the District of Mackenzie. Pugh (1983) demonstrated that the Hare Indian, Ramparts and Canol formations are condensed westward becoming undifferentiable basinal black shale. He elevated the Horn River Formation to group status and defined it to include the Hare Indian Formation and lateral facies equivalents, the Ramparts Formation and the Upper Devonian Canol Formation. The condensed sequence of black shales to the west was referred to the Horn River Formation. Pugh (1983) suggested that the Canol Formation is lithologically similar to and occupies the same stratigraphic position as the Muskwa Member of the Horn River Formation.

Most workers have considered the Horn River Formation to be of Middle Devonian (Givetian) age (Douglas and Norris, 1960; Belyea and Norris, 1962; Gray and Kassube, 1963; House and Pedder, 1963; McLaren and Norris, 1964; Griffin, 1965, 1968; Norris, 1965; Vopni and Lerbekmo, 1972; Chatterton, 1978; Williams, 1983). However, Fuller and Pollock

(1972) obtained Late Devonian conodonts from a part of the Horn Plateau Formation which they considered to be a later fissure filling, thus raising some questions about the age of the overlying Horn River Formation. The Muskwa Formation is generally regarded as being of Late Devonian (Frasnian) age (Griffin, 1965, 1968; Bassett and Stout, 1968; Williams, 1983).

E. Hay River and Fort Simpson formations

The geology of the Hay River area was first discussed by McConnell (1891) and Cameron (1917). Later, Cameron (1918, 1922) proposed the terms "Hay River shale" and "Hay River limestone" for the Upper Devonian strata exposed along Hay River (Fig. 4). The "Hay River shales" included all the strata exposed on the river, up to the first major limestone unit at the base of Louise Falls. The "Hay River limestones" included all the Upper Devonian beds exposed on Hay River above this point.

At the same time Cameron (1918) introduced the name "Simpson shales" for 45.7 m (150 ft) of soft, grey, partly calcareous shales containing a Portage fauna, in the vicinity of Fort Simpson (Fig. 4). He believed that the shales at Fort Simpson were older than those exposed along Hay River. However, more recent work has shown that these shale units are part of the same lithological sequence (Belyea and McLaren, 1962; House and Pedder, 1963). Therefore, some revision of the formational nomenclature is needed since the terms Hay River Formation and Simpson (=Fort Simpson) Formation were originally proposed for two units which are now known to be equivalent in age and part of the same lithologic sequence. This was pointed out by Crickmay (1953, p. 11) who suggested that

> "... one formation name comprised the entire Devonian section on Hay River, namely, Hay River Formation. It has of course, long since become evident that this use of a formation name is incorrect. The lower part of the shales on Hay River can not be included for they are the exact equivalent of part of the previously named Simpson Formation."

Bassett (1952) was the first to apply the name Hay River Formation to the shale and carbonate sequence between the Slave Point Formation and the sandstone unit at the base of Alexandra Falls. Crickmay (1953) suggested that the term Hay River Formation should be restricted to the 161.5 m (530 ft) of strata exposed on Hay River between the "lowest shell bed" and the base of the massive limestone unit at Louise Falls. Crickmay (1953) referred the

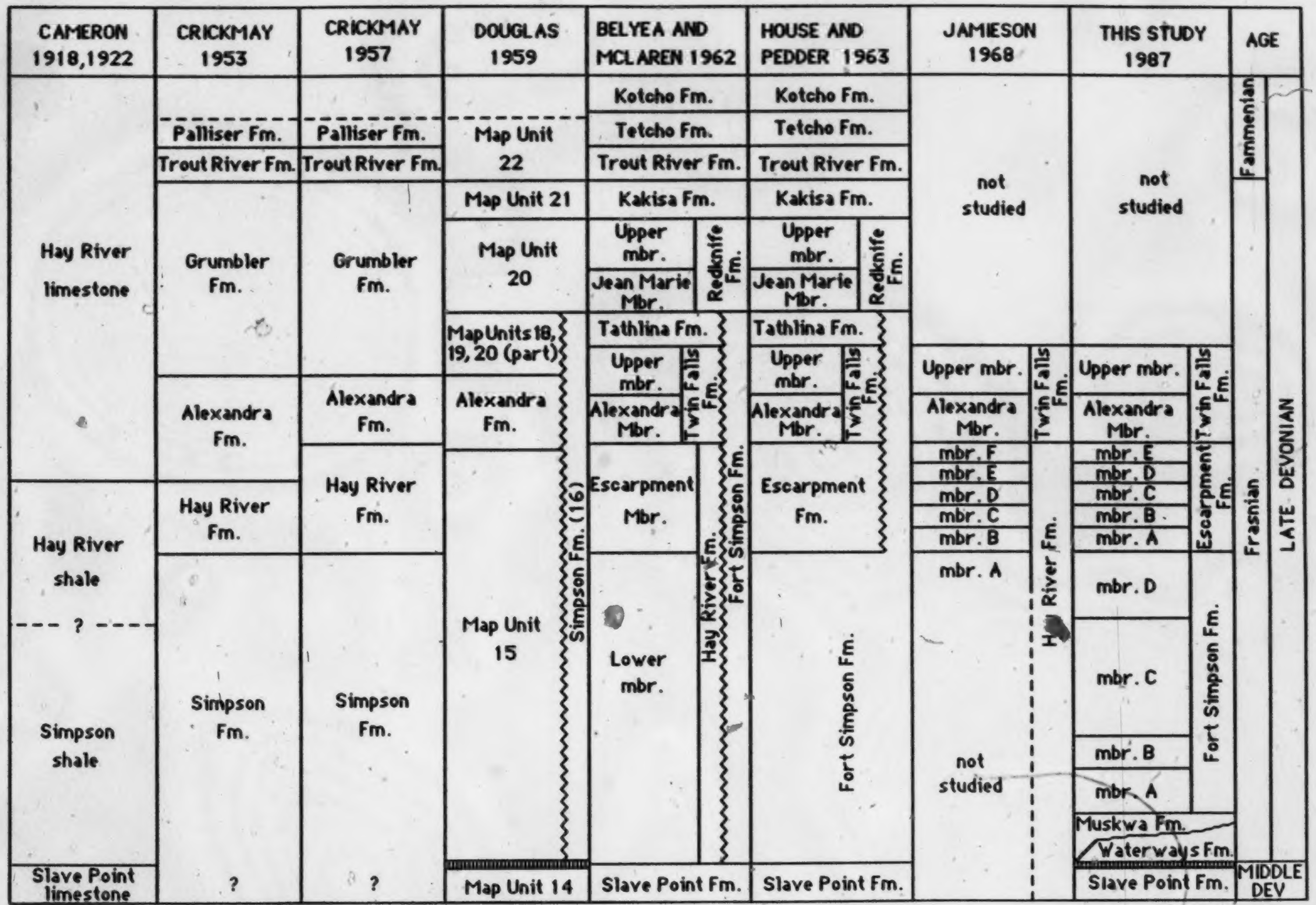


Figure 4. History of stratigraphic nomenclature in the study area.

shales below the lowest shell bed to the Simpson Formation. He proposed the name Alexandra Formation for the 78 m (225 ft) of limestone exposed at Alexandra and Louise Falls (Fig. 4). The limestones outcropping upstream from Alexandra Falls were placed in the Grumbler Formation. Crickmay (1957) redefined the base of the Alexandra Formation to exclude the 1.8 m (6 ft) of sandstone and siltstone exposed at the base of Alexandra Falls.

The Hay River and Simpson formations of Crickmay (1957) correspond to Douglas's (1959) Map Unit 15 except that Douglas included an extra 3.7 m (12 ft) of the underlying Hay River Formation in the Alexandra Formation (Fig. 4). Douglas (1959, p. 20) commented on the stratigraphic nomenclature problems in the area, stating that

> "The Hay River shales were considered to be underlain by the Simpson shale, based on correlation with the Fort Simpson region, and these beds, in turn, by the Slave Point formation of Middle Devonian age. These concepts have not been entirely validated by the present study. The simple two-fold subdivision is not applicable throughout the map area, as the top of the predominantly shale part on Hay River, the Hay River shale (map-unit 15), falls within the shale succession of the Simpson formation (map-unit 16)."

Douglas and Norris (1961) proposed that Cameron's (1918) term, "Simpson shale", be referred to the term Fort Simpson Formation because the term Simpson was previously occupied.

Belyea and McLaren (1962) designated the type section of the Fort Simpson Formation in the Briggs Turkey Lake No. 1 well (61° 07' N, 120° 22' W) where it occurs between 237.7 m (780 ft) and 829 m (2,720 ft). There the Fort Simpson Formation consists of greenish grey to grey, variably calcareous and quartzose, mudstones and shales. As defined by Belyea and McLaren (1962) the Fort Simpson Formation, west of Kakisa River, includes the stratigraphic interval occupied by the Hay River, Twin Falls and Tathlina formations, as developed in the Hay River area. The upper boundary of the formation was drawn at the base of the Jean-Marie Member of the Redknife Formation. However, they suggested that usage of the term should be extended to include possible stratigraphic equivalents of the Redknife and Kakisa formations. The lower boundary in the type well was placed at the top of the dark brownish grey to black shales of the Middle Devonian Horn River Formation as defined by Belyea and Norris (1962).

Torrie (1972) considered the Fort Simpson Formation to include strata up to the top of the Trout River Formation. House and Pedder (1963), Law (1971) and de Wit *et al.* (1972) considered the Fort Simpson Formation to be equivalent to the strata up to the top of the Wabamun Group. Toward the southeast, in northeastern British Columbia, strata of the Fort Simpson Formation grade into black shales of the Besa River Formation (Pelzer, 1966).

Belyea and McLaren (1962) redefined the Hay River Formation to include all the strata exposed on Hay River below the Alexandra Formation as defined by Crickmay (1957). In addition, they included the 164 m (539 ft) of shale that overlies the Slave Point Formation in Frobisher Hay River No. 4 well (60° 42' N, 115° 52' W). The total thickness of the Hay River Formation at the type sections was placed at 396 m (1300 ft). They divided the Hay River Formation into an informally designated, "lower member" and an upper Escarpment Member (Fig. 4). The lower member, which corresponds approximately to the Simpson Formation of Crickmay (1953, 1957), comprises variably calcareous, greenish grey mudstones and shales, with widely scattered, thin beds of argillaceous limestone, included 122 m (399 ft) in outcrop and a further 164 m (539 ft) in Frobisher Hay River No. 4 well.

The type section of the Escarpment Member comprises 111 m (364 ft) of olive grey calcareous mudstones, and thin bedded argillaceous limestones with some bioclastic, biohermal and biostromal limestone bodies (Belyea and McLaren, 1962). They placed the lower boundary of the Escarpment Member at the base of a prominent 1.2 m (4 ft) thick, greenish grey argillaceous limestone containing abundant corals and brachiopods. They informally referred to this unit as the "*Schizophoria* bed" and noted that it was the lowest coral bearing unit exposed on Hay River.

House and Pedder (1963) raised the Escarpment Member to formational status, abandoning the term Hay River Formation and adopting the term Fort Simpson Formation for the shales below the Escarpment Formation (Fig. 4). It is assumed that they revised the nomenclature because of Cameron's (1918) miscorrelation of the Fort Simpson and Hay River formations.

Richmond (1965) followed the definition of Belyea and McLaren (1962) of the upper boundary of the Hay River Formation but redefined the base of the formation. He placed the base of the Hay River Formation at the top of the uppermost bituminous shale of the Horn River Formation, which he interpreted to overlie the Slave Point Formation in the Hay River area.

Jamieson (1967) excluded the Escarpment Member from the Hay River Formation (Fig. 4) because of miscorrelations of that unit with overlying limestones of the Alexandra Member of the Twin Falls Formation by Douglas (1959) and Belyea and McLaren (1962). In her unpublished work (Jamieson, 1967; Table 3), she divided the Hay River Formation into five members (in ascending order); the "Lowest", Sandwich, Enterprise, Louise Falls, and Lookout members. These terms were not clearly defined and were subsequently replaced by six informal members (Fig. 4) designated A to F (Jamieson, 1968). She noted the occurrence of a coral bearing limestone 1.9 m (6.3 ft) above the base of member B, containing *Alveolites* sp. and *Phillipsastrea* sp., which she considered the lowest coral bearing unit of the Hay River Formation. However, it is not clear if this bed corresponds to the lowest shell bed as described by Crickmay (1953) and/or the lowest coral bed described by Belyea and McLaren (1962). If these beds are the same, then Jamieson's (1968) members B to F correspond to the Escarpment Member of Belyea and McLaren (1962). Presumably, Jamieson's (1968) member A included the strata down to the base of the formation.

Mitchell (1970, 1972) studied outcrops of the Escarpment Member, as defined by Belyea and McLaren (1962), near Enterprise. His studies focused mainly on the paleoecology of the unit. Douglas (1974) produced a regional geology map of the Hay River and Trout River areas. Although he employed the terminology of Belyea and McLaren (1962), he showed strata of the Hay River Formation enveloping a relatively thin, wedge-shaped Escarpment Member. The Escarpment Member is thus shown to be separated from the Twin Falls Formation by a variable thickness of undifferentiated Hay River Formation. According to Williams (1977), the Escarpment Member was used by Douglas (1974) to denote only the lenticular unit of limestone which forms Louise Falls and the escarpment near Escarpment Lake. As such, it differs markedly from the definition proposed by Belyea and McLaren (1962).

Williams (1977) studied geophysical logs of the Hay River Formation and used them to illustrate the presence of clinoforms in the formation. His correlations were based on the geophysical character of the log profiles. He suggested that some of the lowest beds in the Hay River Formation could be termed, progressing from east to west: (1) the Waterways Member, for shales with limestone bands, (2) the Muskwa-Waterways Member, for the above plus interbeds of radioactive shale, and (3) the Muskwa Member, for predominantly radioactive shale. However, these terms were not properly defined and only add to the complexity of the nomenclature that exists for these strata. Meijer Drees (1986, Fig. 1) appears to have followed the work of Williams (1977). It is not clear, however, if he included the Muskwa Member as part of the Hay River Formation or as part of the Waterways Formation or both.

Klapper and Lane (1985), in their study of the conodonts of the Hay River Formation, adopted the terminology of Jamieson (1968) and assumed the Hay River Formation included all the strata from the top of the Slave Point Formation to the top of Jamieson's member F. Although they measured thirteen sections of the formation from outcrops along Hay River, they did not provide detailed stratigraphic correlations or sedimentological interpretations.

Various aspects of the paleontology of the Hay River Formation have been studied by Whiteaves (1891), Kindle (1919), Springer (1926), Warren (1944), Smith (1945), Crickmay (1950, 1952, 1953, 1957), Warren and Stelck (1956), McLaren (1959), McLaren *et al.* (1962), Pedder (1960), House and Pedder (1963), Stearn (1966), McGregor and Owens (1966), Braun (1968), Mitchell (1970, 1972), Apon (1980), and Klapper and Lane (1985), McLean (1984). Most studies, however, included only the upper part of the Hay River Formation.

F. Twin Falls Formation

The name Twin Falls Formation was proposed by Belyea and McLaren (1962) for approximately 159 m (521 ft) of "reefoid" limestone lying between the Hay River Formation and the Tathlina Formation (Fig. 4). The type section of the formation is exposed, from the top of the Hay River Formation at the base of Alexandra Falls, to a point 1.6 km (1 mi) above Grumbler Rapids (Belyea and McLaren, 1962). A supplementary section was designated in Murphy Canada Alexandra Falls No. 2 well (60° 15' N, 116° 34' W).

Belyea and McLaren (1962) divided the Twin Falls Formation into the Alexandra Member and an informally designated "upper member" (Fig. 4). The Alexandra Member corresponds to Crickmay's (1957) Alexandra Formation but excludes the upper 11 m (36 ft) of his definition. The upper member consists of 128 m (420 ft) of variably bioclastic, reefoid and biostromal limestone with some quartz sandstone and siltstone and shaley units (Belyea and McLaren, 1962). A detailed study of the Alexandra Member was provided by Jamieson (1967, 1968, 1971).

Belyea and McLaren (1962) proposed a mid-Frasnian age for the Twin Falls Formation and suggested correlation with part of the Ireton Formation in the subsurface. They also noted that the Twin Falls Formation extends to the south and southeast where it becomes part of the Grosmont Formation. Norris (1963, Fig. 3) and Cutler (1983) indicated that the Twin Falls Formation is equivalent to the upper part of the Mikkwa Formation and the lower part of the Grosmont Formation in the Mikkwa-Peace Rivers area of northern Alberta.

G. Hay River Formation and equivalent strata

Belyea and McLaren (1962), Norris (1965) and Crickmay (1966) suggested that the lower part of the Hay River Formation is equivalent to the Firebag Member of the Waterways Formation. In addition, Crickmay (1966), Norris (1973), and Norris and Uyeno (1983) suggested equivalence with the Peace Point Member of the Waterways Formation. Belyea and McLaren (1962) argued that the lower member of the Hay River Formation correlated with the Waterways, Beaverhill Lake and Cooking Lake formations.

Based on a detailed ostracode zonation, Braun (1968) correlated the Upper Devonian strata, exposed along Hay River and in Frobisher Hay River No. 4 well, with the Upper Devonian strata in northeastern Alberta, in the Bear Biltmore No. 1 well (7-11-87-17-W4M). He suggested that the lower member of the Hay River Formation was equivalent to the Waterways and Cooking Lake formations and the lower part of the Ireton Formation. The Escarpment Member was considered to be the equivalent of the upper part of the Ireton Formation and, possibly, the Grosmont Formation. Braun (1968) noted that in the Hay River area only the beds belonging to the youngest part of the basal Frasnian microfaunal zone (*DFr* 1) are present above the Middle Devonian Slave Point Formation. He suggested that the missing strata were either removed or were not deposited in this area.

Norris (1973, Fig. 3) indicated that the lower member is equivalent to the Waterways Formation and most of the Ireton Formation. Williams (1977), based on inferred clinoform log markers, suggested that the 390 m of Hay River shale at the type section is equivalent to a much thinner interval within the basal part of the Fort Simpson Formation and the upper part of the Muskwa Formation. He also indicated that the basal part of the Hay River Formation is equivalent to the upper part of the Horn River Formation. Braun and Lethiers (1982) proposed equivalence with the Waterways and Cooking Lake formations and the lower part of the Ireton Formation.

The Escarpment Member has been correlated with the Duvernay Formation and the lower part of the Ireton Formation (Belyea and McLaren, 1962), with the upper part of the Ireton Formation and the lower part of the Mikkwa Formation (Norris, 1973), and with the upper part of the Ireton Formation and part of the Grosmont Formation (Braun and Lethiers, 1982). Cutler (1983, Fig. 26) indicated that the Hay River Formation is equivalent to the Ireton Formation and is overlain by the Lower Limestone Member of the Mikkwa Formation in the subsurface of the Mikkwa-Peace Rivers area. Belyea (1964) correlated the Duvernay Formation of north central Alberta with the upper part of the Hay River Formation and part of the Fort Simpson Formation.

H. Nature of upper boundary - Slave Point Formation

At present the placement of the Middle/Upper Devonian boundary in western Canada is unresolved. Norris and Uyeno (1983) noted, however, that most workers have tentatively and traditionally selected the base of the Waterways Formation as the base of the Upper Devonian. A distinctive faunal break occurs at the boundary between the Slave Point and Waterways formations, marked by the abrupt appearance of new genera and species in the Waterways Formation. Norris and Uyeno (1983) suggested that this break may be equivalent to faunal breaks recognized between the Slave Point and Waterways (=Beaverhill Lake) formations by McGill (1966) and between the Slave Point and Hay River formations by Norris (1965) and Belyea and McLaren (1962).

Warren and Stelck (1949) placed the Middle/Upper Devonian boundary at the unconformity at the top of the Slave Point Formation. Law (1955), Douglas (1959) and Norris (1965, 1973) indicated that the contact between the Hay River and Slave Point formations is unconformable or at least disconformable. Braun (1968), however, argued that the contact was disconformable on the basis of changes in the ostracode fauna across the contact. Skall (1975) noted that the disconformity proposed by Braun (1968) possibly exists in the Pine Point area. However, he argued that there was no evidence of karst topography at the contact and considered this evidence against an unconformity between the formations. Williams (1977) considered the contact to be gradational. Rhodes *et al.* (1984) suggested that there is a possible unconformable relationship between the two formations in the Pine Point area.

Carrigy (1959) considered the contact between the Slave Point and Beaverhill Lake formations (=Waterways Formation), in the McMurray area of northeastern Alberta, to be paraconformable, although he gave no reasons for this. Belyea (1971) noted that the Slave Point Formation, in the area of the Tathlina Uplift, is unconformably overlain by Upper Devonian shales. Crawford (1972) considered the contact in northern Alberta between the Slave Point Formation and Beaverhill Lake Formation (=Waterways Formation) to be disconformable, being marked by a sharp faunal and lithological break. However, he suggested that nondeposition, not erosion, was the major factor determining the nature of the contact.

Featherstone (1982), based on a study of ostracodes from the Slave Point Formation in northern Alberta, concluded that the top of the formation is marked by an unconformity. He noted subtle erosional features at the top of the Slave Point Formation and suggested that there were 1 to 1.5 ostracode biozones missing at the Slave Point-Waterways formations contact. However, he suggested that this represented a short time interval. In contrast, Meijer Drees (1986) suggested that the Slave Point Formation is sharply but conformably overlain by shaley late Middle Devonian beds.

A number of workers have reported the occurrence of breccias in the Slave Point Formation of northeastern Alberta (Norris 1963, 1965; Crawford, 1972; Norris and Uyeno 1983; Park, 1984; Park and Jones, 1985). Norris (1963) and Park and Jones (1985) presented evidence for an unconformity at the top of the Slave Point Formation in this area. However, Norris and Uyeno (1983) noted that the erosive event responsible for the unconformity was probably of short duration since no conodont zones are missing.

I. Revised stratigraphy

Since the original work by Cameron (1917, 1918, 1922) the stratigraphic nomenclature of the Upper Devonian basin-filling shales and carbonates in the Hay River area has been extensively debated. Subsequent workers have been split into two factions; Crickmay (1953, 1957) and House and Pedder (1963) favoured retention of the term Fort Simpson Formation while Belyea and McLaren (1962) and Jamieson (1967, 1968) suggested that these strata should be assigned to the Hay River Formation. These studies relied mainly on observations of the upper part of the Upper Devonian sequence which is exposed along Hay River. The lower part of this succession received much less attention due to the lack of outcrops and drill core.

After examining eighteen complete cores from Upper Devonian strata in the area immediately west of the type section of the Hay River Formation, it became evident that: (1) a more detailed subdivision of the strata between the Slave Point and Twin Falls formations was possible, (2) the Waterways and Muskwa formations, recognized by Griffin (1965, 1968) in northeastern British Columbia and northern Alberta, are present in the study area, (3) the strata referred to the Escarpment Member of the Hay River Formation by Belyea and McLaren (1962) are lithologically distinct and widely mappable; This rock unit should, therefore, be elevated to formational status, following the work of House and Pedder (1963), and (4) the strata previously assigned to the lower member of the Hay River Formation by Belyea and McLaren (1962), share a close lithologic affinity with the Fort Simpson Formation and should, therefore, be assigned to that formation; this agrees with the suggestion of Crickmay (1953, 1957) and House and Pedder (1963).

During the field mapping it was noted that a number of the stratigraphically lowest sections on Hay River could not be tied into the stratigraphic cross-sections due to incomplete exposure along the river. The complete nature of the drill core, however, allowed all of the measured outcrop sections to be accurately tied into the stratigraphic cross-sections. Lithologic units, in each of the cores and measured sections, were correlated on a bed by bed basis in order to accurately establish formation and member boundaries.

Two of the cores examined, HW-79-9 and HW-79-10 (Fig. 1), encompass the entire sequence between the Slave Point and Twin Falls formations. The core from HW-79-9 (60° 35' 30" N; 116° 14' 35" W) contains the most representative and complete section of the Upper Devonian strata examined in this study and, therefore, is herein designated as the reference section (Fig. 5). In the reference section the Upper Devonian strata can be divided into four distinctive formations (Fig. 5), which are: (1) the Waterways Formation (8.8 m thick), (2) the Muskwa Formation (3.3 m thick), (3) the Fort Simpson Formation (253.2 m thick), and (4) the Escarpment Formation (105.8 m thick).

Comparison of the formations in terms of their gross lithologic composition clearly highlights the differences between the four formations (Fig. 6). The mappability, distribution, and thickness of these formations can be demonstrated by five stratigraphic cross-sections

(Fig. 7) which use the base of the Slave Point Formation (Amco Member) as a datum (Figs. 8 to 12). The base of the Slave Point Formation was selected as the datum because: (1) an isopach map of the Slave Point Formation revealed an irregular thickness distribution (Fig. 13), indicating that either the top and/or the bottom of the formation is an irregular surface, (2) cross-sections constructed using the base of the Slave Point Formation as a datum showed that the upper surface of the Slave Point Formation has an irregular topography; this would explain the thickness variations revealed by the isopach map, and (3) Skall (1975), Lantos (1983), and Rhodes *et al.* (1984) considered the Amco Member of the Slave Point Formation to be a time stratigraphic marker.

By matching available geophysical logs to the drill cores examined, it was determined that formation and member boundaries could be accurately picked on the logs. These picks could also be extended to geophysical logs for which core was not logged and correlations could be extended into the subsurface with certainty (Fig. 12).

Thickening and thinning of the Slave Point, Waterways and Muskwa formations and the lower part of the Fort Simpson Formation, show a close correlation with each other. Successive formations and members were not isopached due to the progressive loss of control points upward in the section. This is the result of Pre-Cretaceous erosion which has cut deeper into the strata toward the northeast (Figs. 8 to 12).

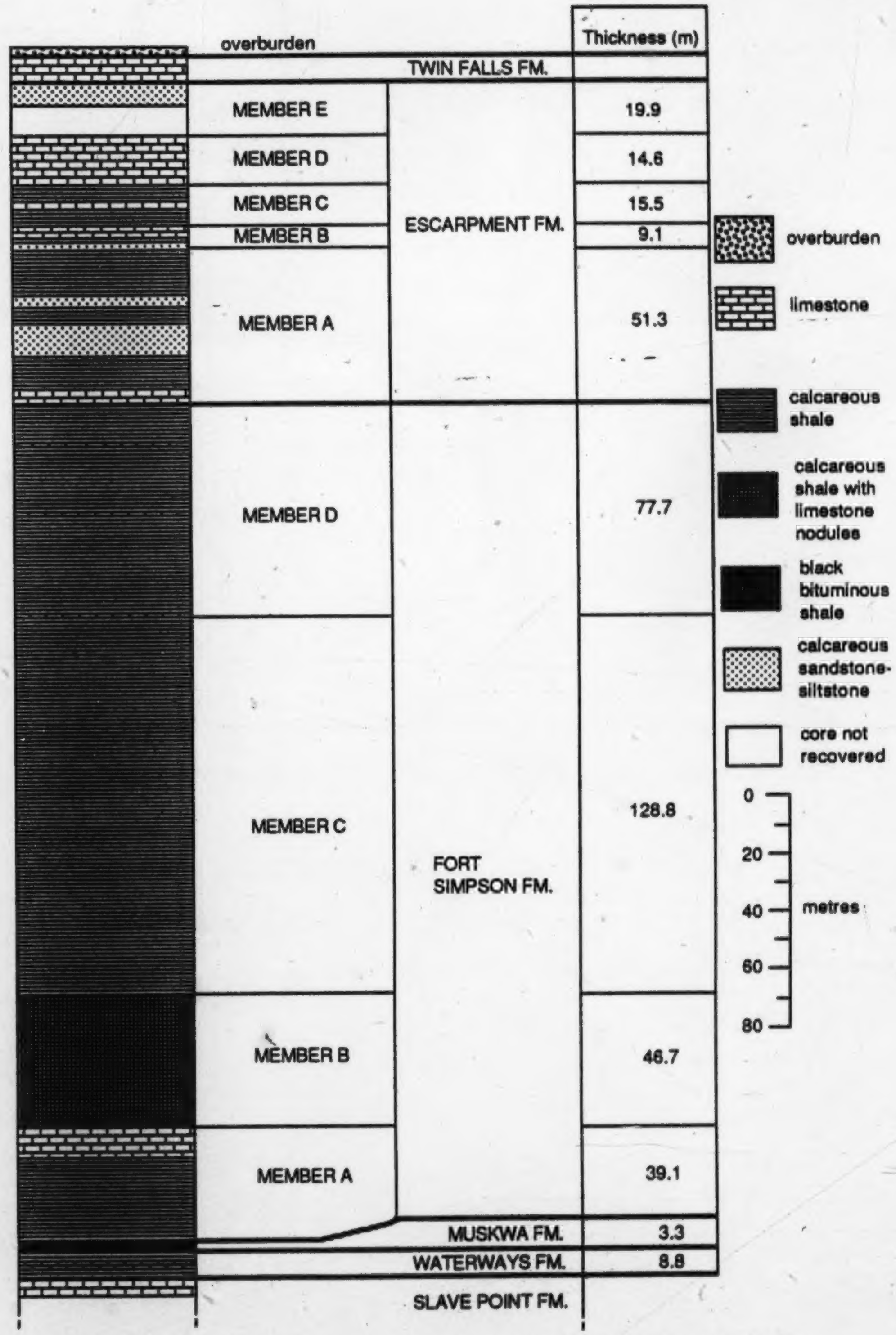


Figure 5. Schematic illustration of subdivisions of Upper Devonian strata in the reference section HW-79-9.

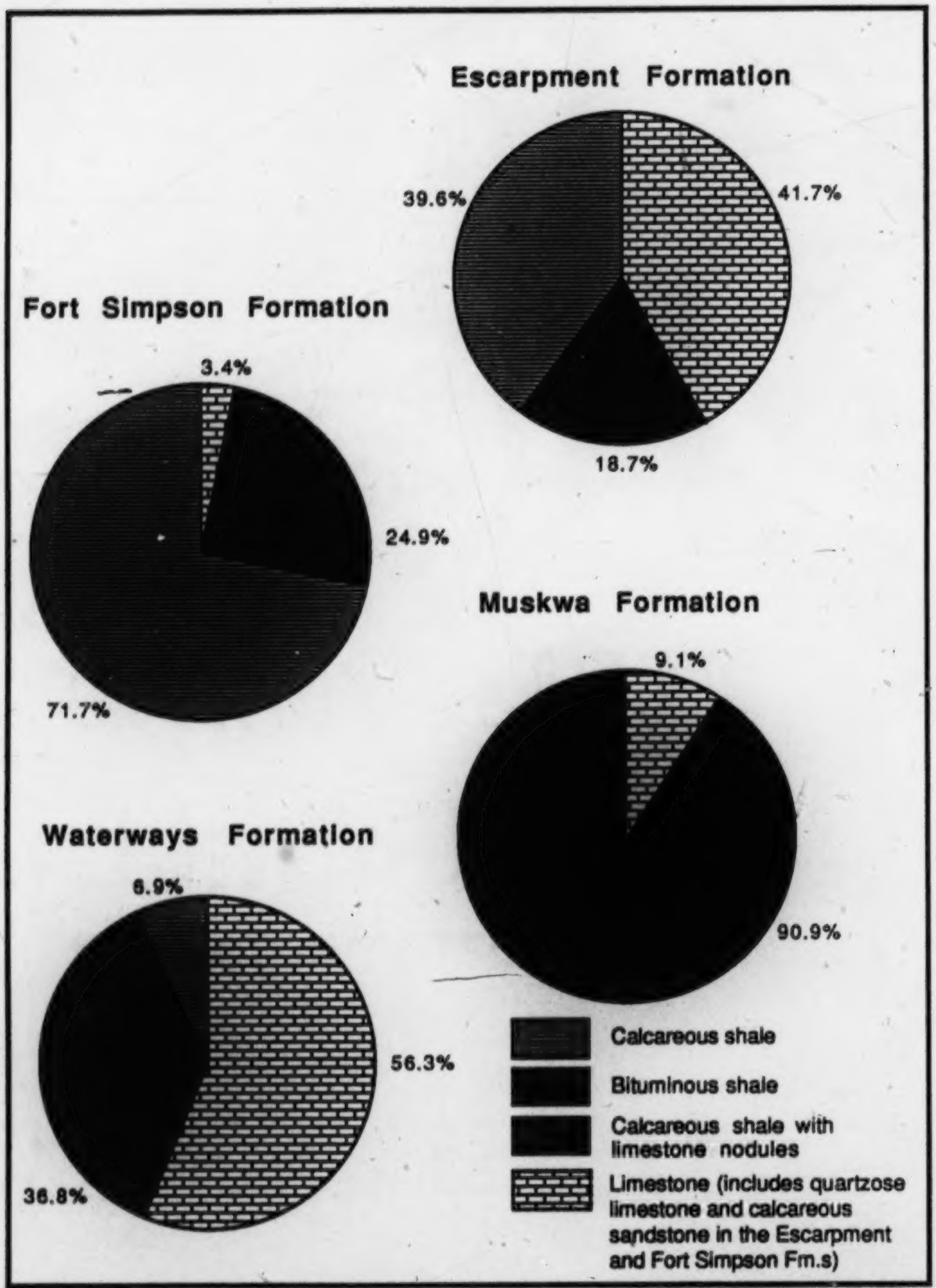


Figure 6. Breakdown of formations in the reference section HW-79-9 by percentage of gross component lithologies. Percentages based on thickness of component lithologies in each.

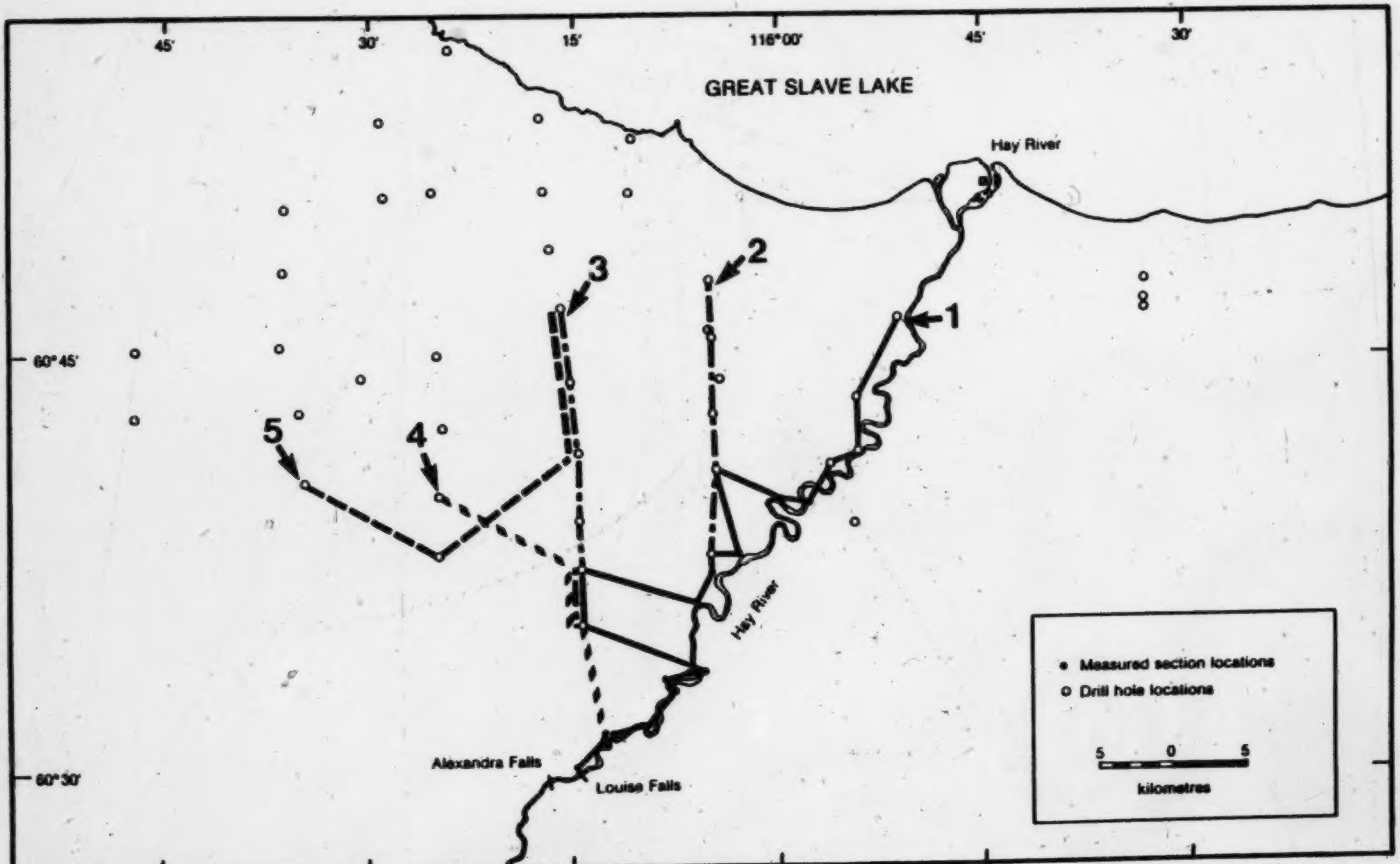


Figure 7. Map showing the locations of lines of stratigraphic cross-sections.

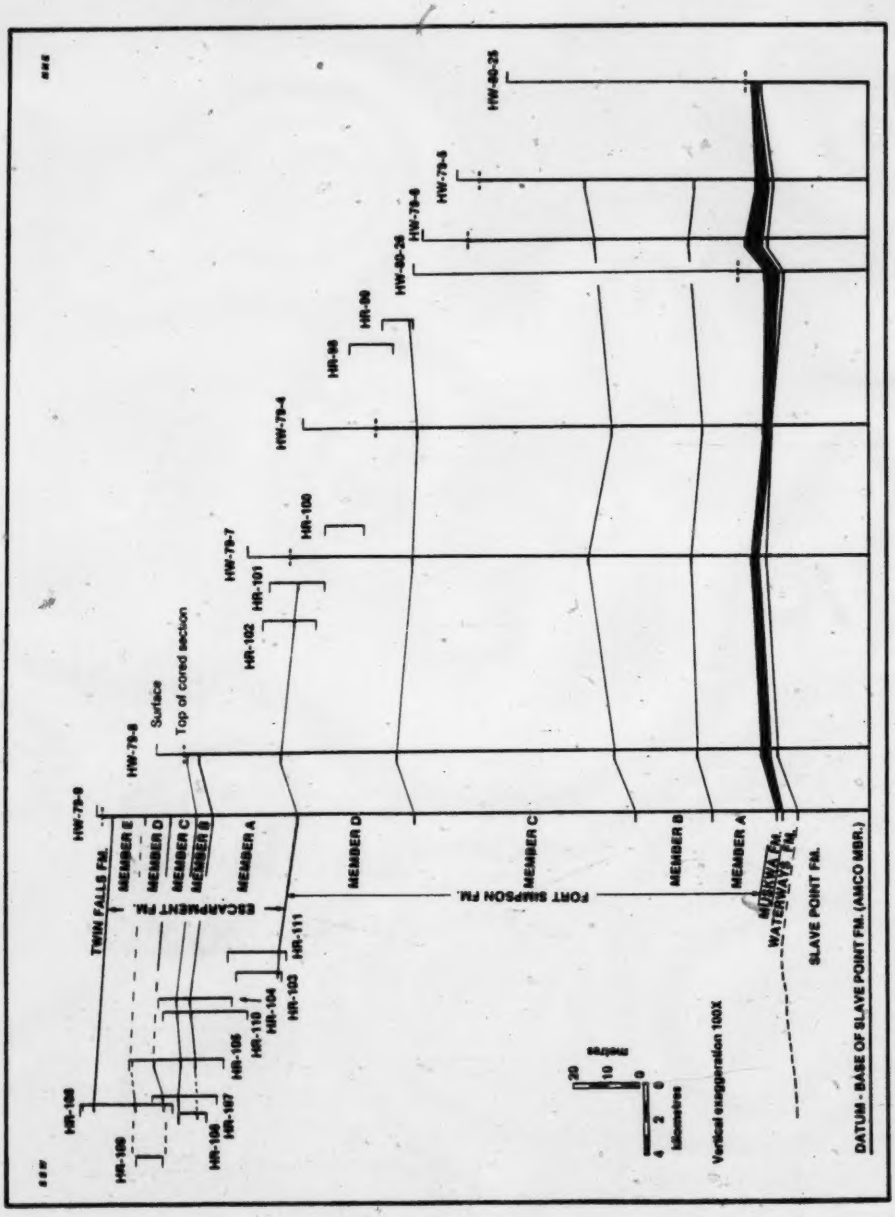


Figure 8. Stratigraphic stick section No. 1 showing correlation and subdivision of strata in the study area.

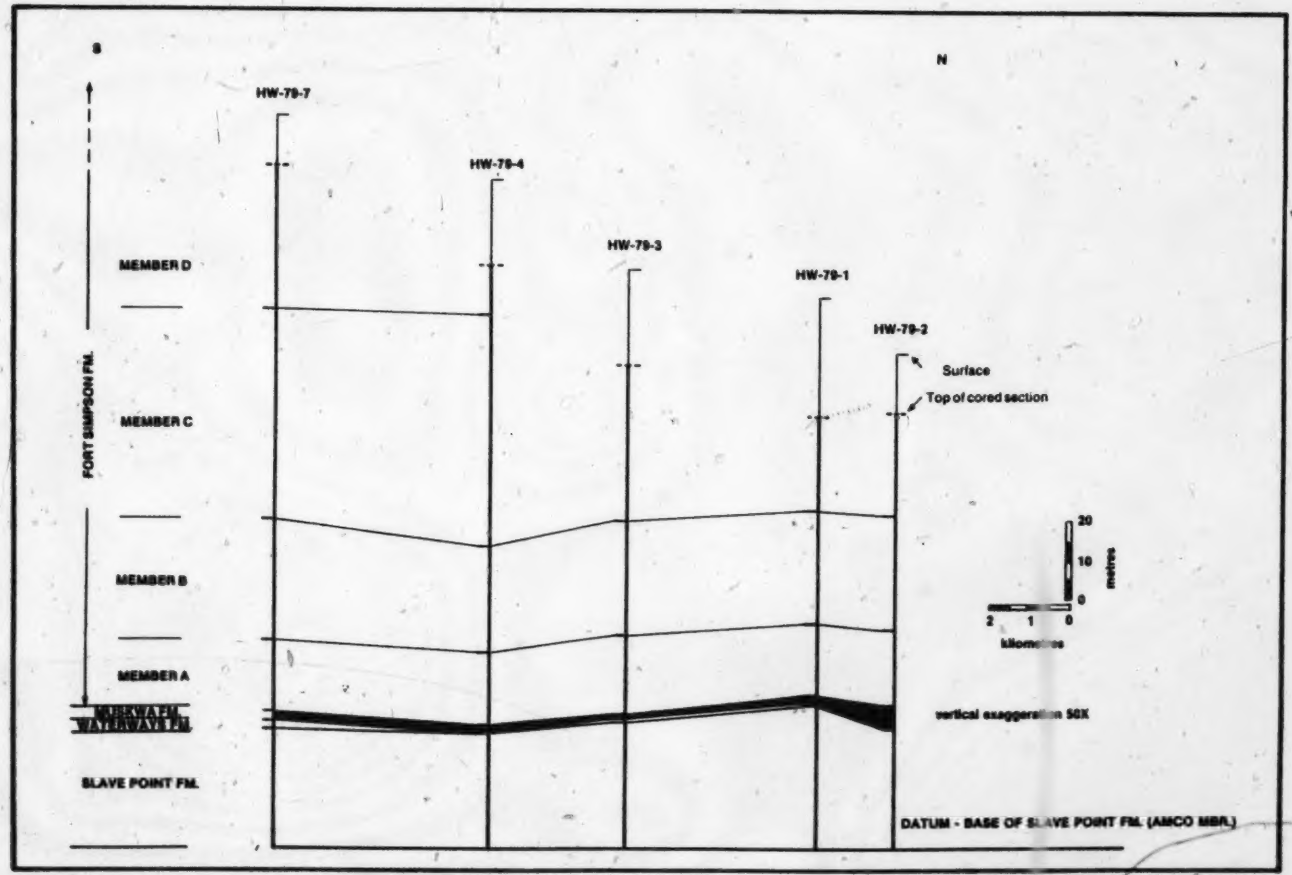


Figure 9. Stratigraphic stick section No. 2 showing correlation and subdivision of strata in the study area.

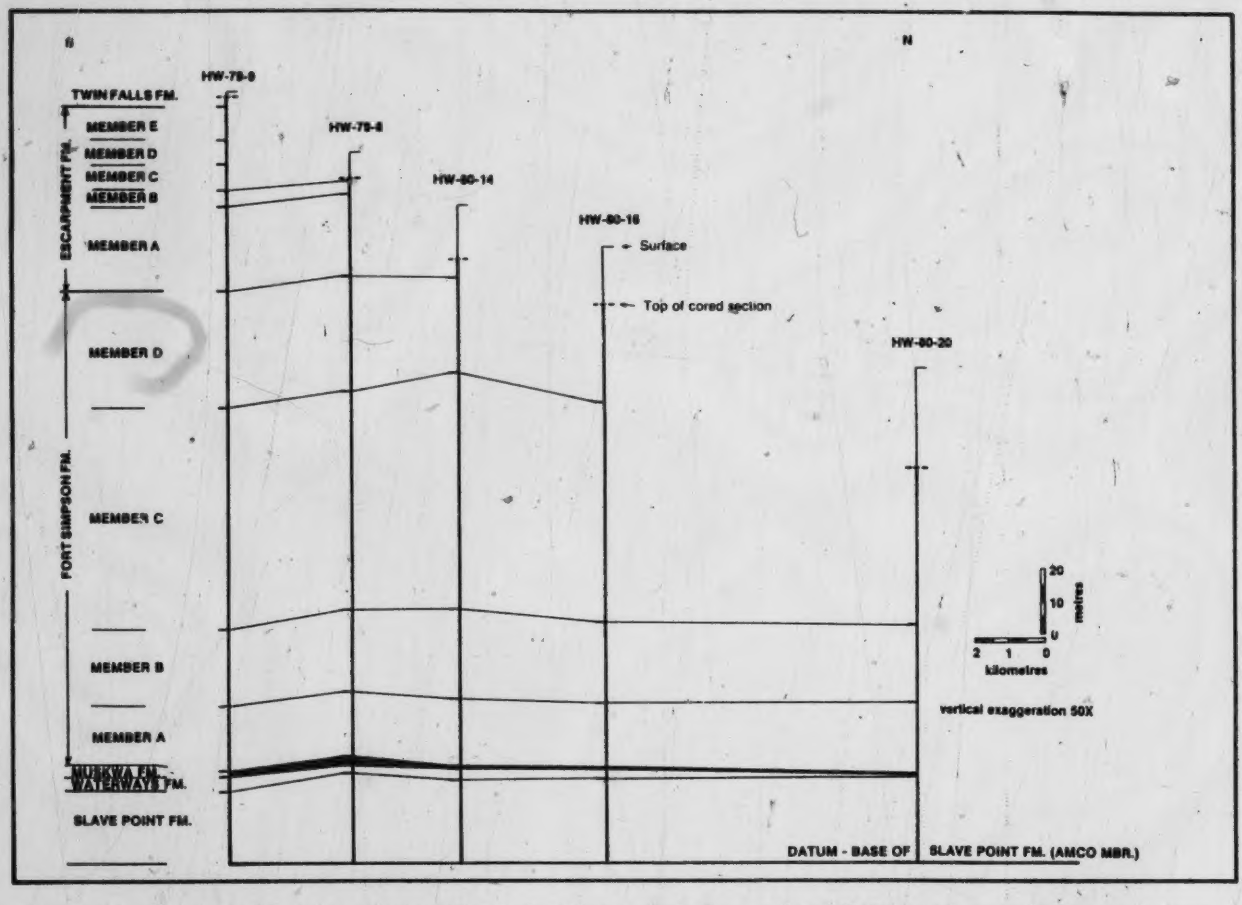


Figure 10. Stratigraphic stick section No. 3 showing correlation and subdivision of strata in the study area.

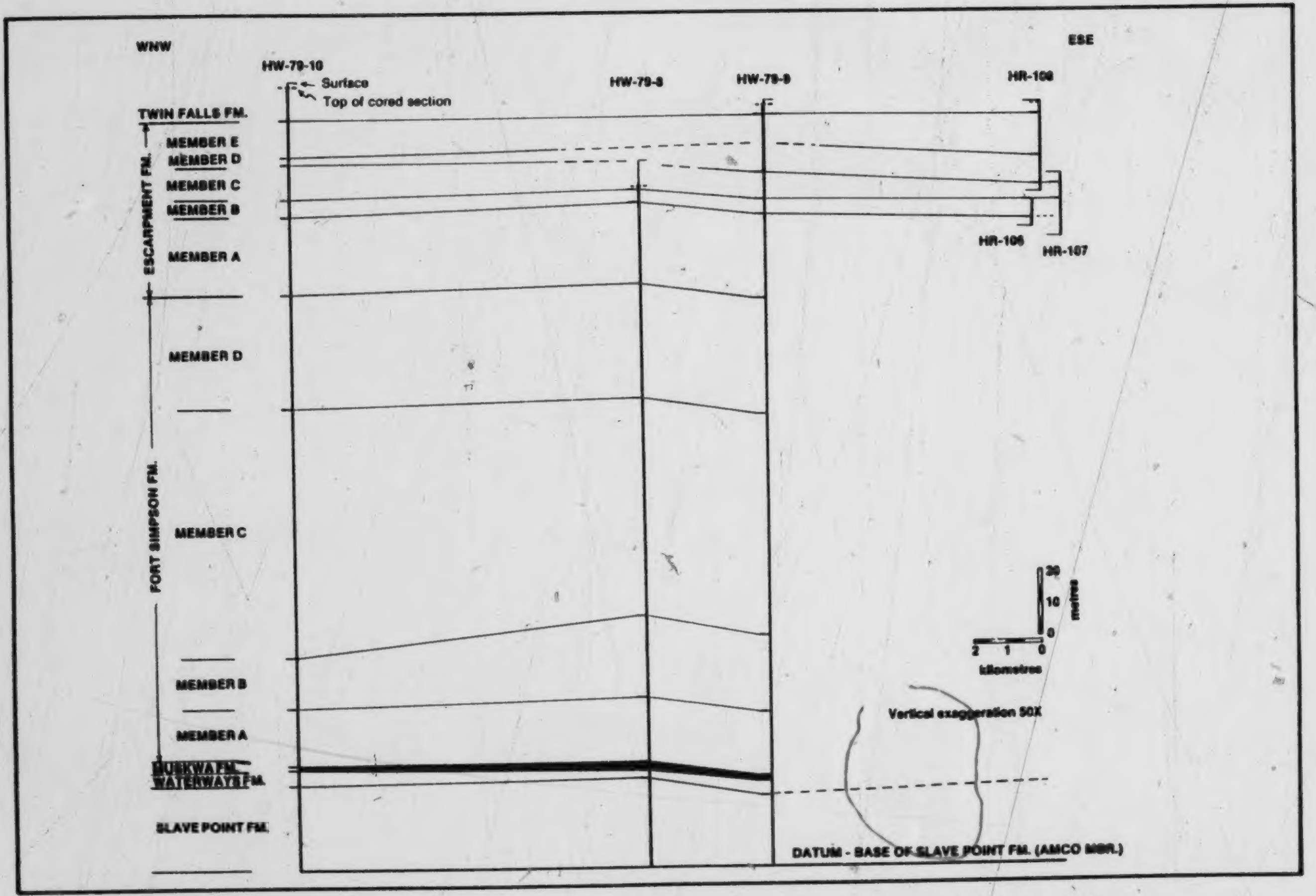


Figure 11. Stratigraphic stick section No. 4 showing correlation and subdivision of strata in the study area.

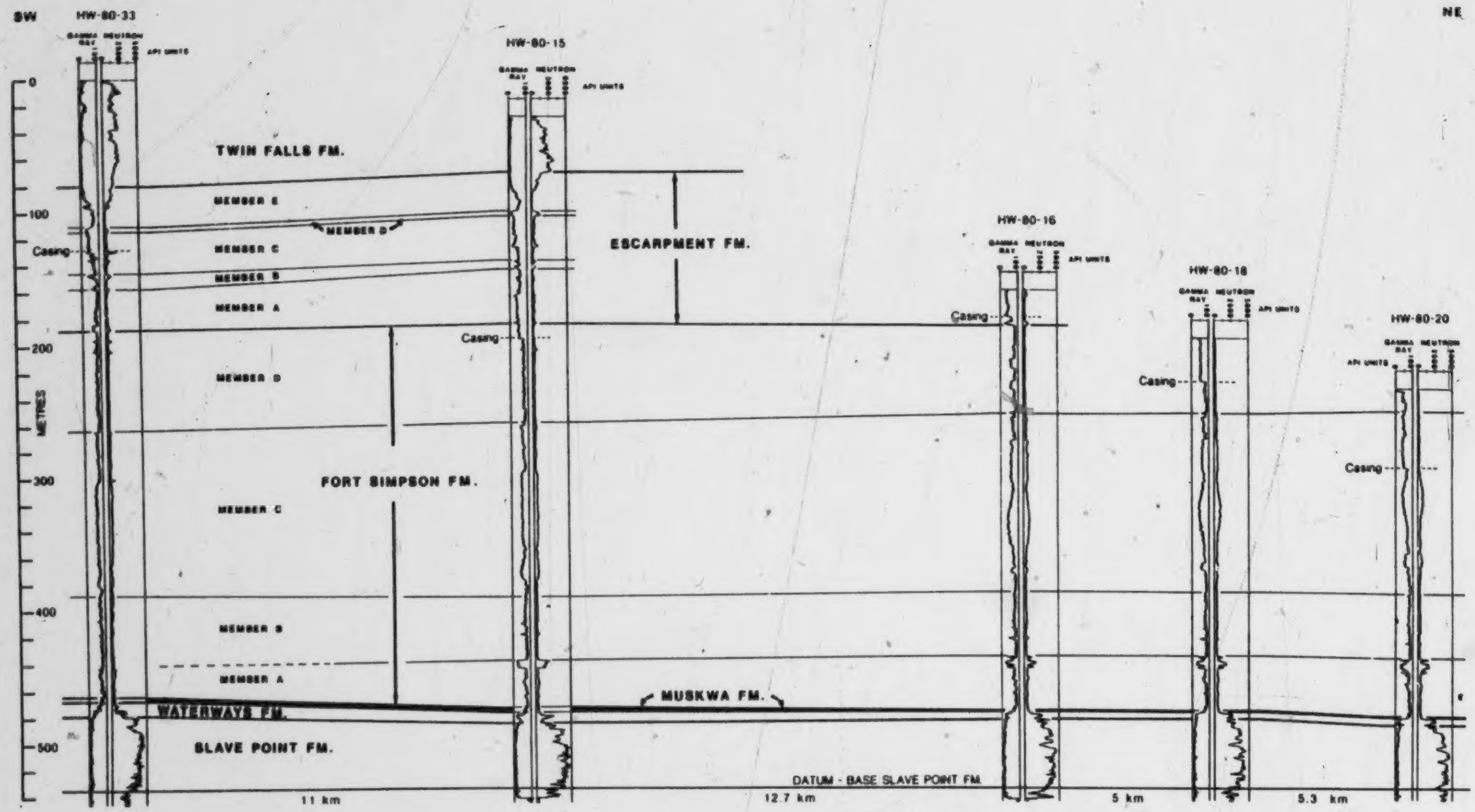


Figure 12. Stratigraphic geophysical log section showing the correlation and subdivision of strata in the study area.

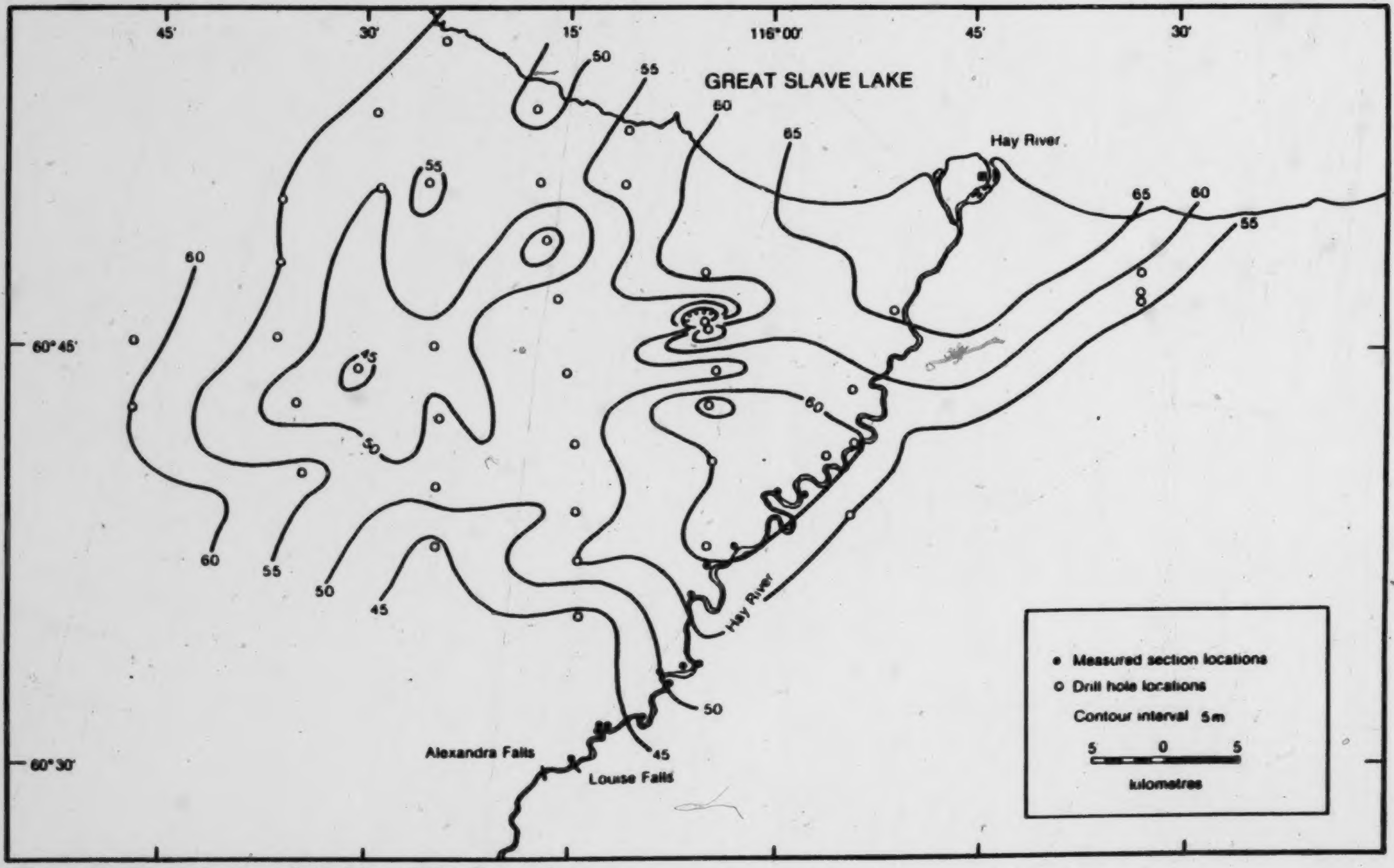


Figure 13. Isopach map of the Slave Point Formation.

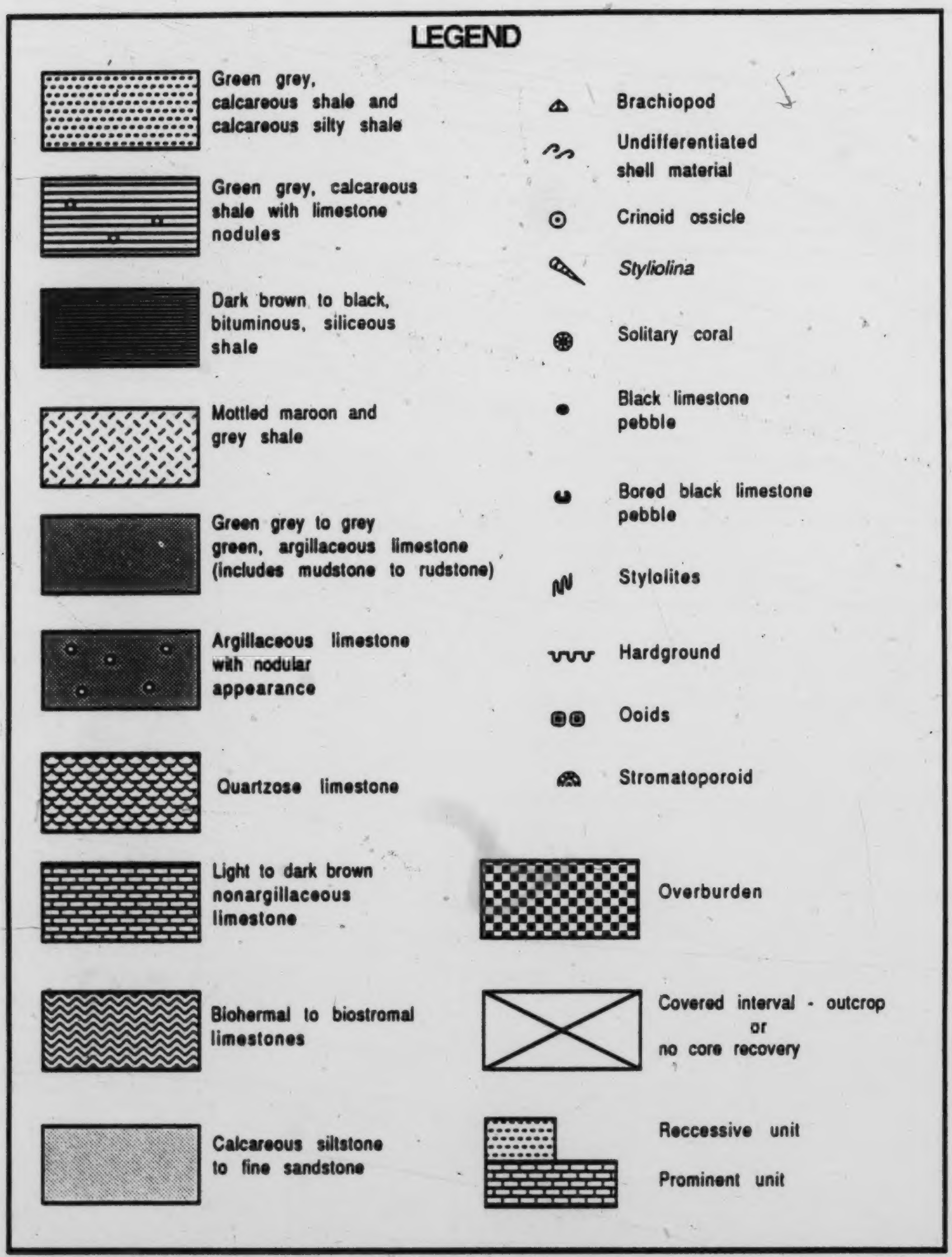

LEGEND
Green grey, calcareous shale and calcareous silty shale
Green grey, calcareous shale with limestone nodules
Dark brown to black, bituminous, siliceous shale
Mottled maroon and grey shale
Green grey to grey green, argillaceous limestone (includes mudstone to rudstone)
Argillaceous limestone with nodular appearance
Quartzose limestone
Light to dark brown nonargillaceous limestone
Biohermal to biostromal limestones
Calcareous siltstone to fine sandstone
Brachiopod
Undifferentiated shell material
Crinoid ossicle
Styliolina
Solitary coral
Black limestone pebble
Bored black limestone pebble
Stylolites
Hardground
Ooids
Stromatoporoid
Overburden
Covered interval - outcrop or no core recovery
Reccessive unit
Prominent unit

Figure 14. Legend of symbols used in detailed sections of the subdivision of strata in the reference section and detailed cross sections of Figures 15, 18 to 21, 23 to 27, 29 to 40 and 42 to 43.

III. SLAVE POINT FORMATION

A. Introduction

In order to characterize the nature of the upper boundary of the Slave Point Formation, the core from the upper 2 to 10 m of the formation in each of the holes was logged. No attempt was made to define the facies within the Slave Point Formation since this has been dealt with extensively by workers in the Pine Point area (Richmond, 1965; Skall, 1975; Rhodes *et al.* 1984).

B. Lower boundary

For the purposes of this study the lower boundary of the Slave Point Formation was placed at the base of the Amco Member of the Slave Point Formation, following the work of Skall (1975) and Rhodes *et al.* (1984). The Amco Member is recognizable, in the area immediately south of Great Slave Lake, by the occurrence of a 3.1 m thick, blue grey, very argillaceous limestone unit, sandwiched between two, 0.1 to 2 m thick, brown sandy micrites with argillaceous wisps (Rhodes *et al.*, 1984). These units, which are variably fossiliferous, contain brachiopods, crinoids and bulbous stromatoporoids. The Amco Member of the Slave Point Formation conformably overlies interbedded dolostones, limestones and shales of the Watt Mountain Formation (Rhodes *et al.*, 1984).

C. Upper boundary

In the reference section HW-79-9 the Slave Point Formation is overlain by strata of the Waterways Formation (Fig. 15). The contact occurs at a depth of 424 m in HW-79-9. The upper part of the Slave Point Formation consists of light brown to grey brown, bioturbated, fossiliferous mudstone to wackestone. The contact between the Slave Point Formation and the Waterways Formation is placed at the first occurrence of green grey, calcareous shale with argillaceous limestone nodules (Fig. 15). Indurated mudstones of the Slave Point Formation grade upward into nodular mudstones with shaley seams and finally into calcareous shales with floating argillaceous limestone nodules.

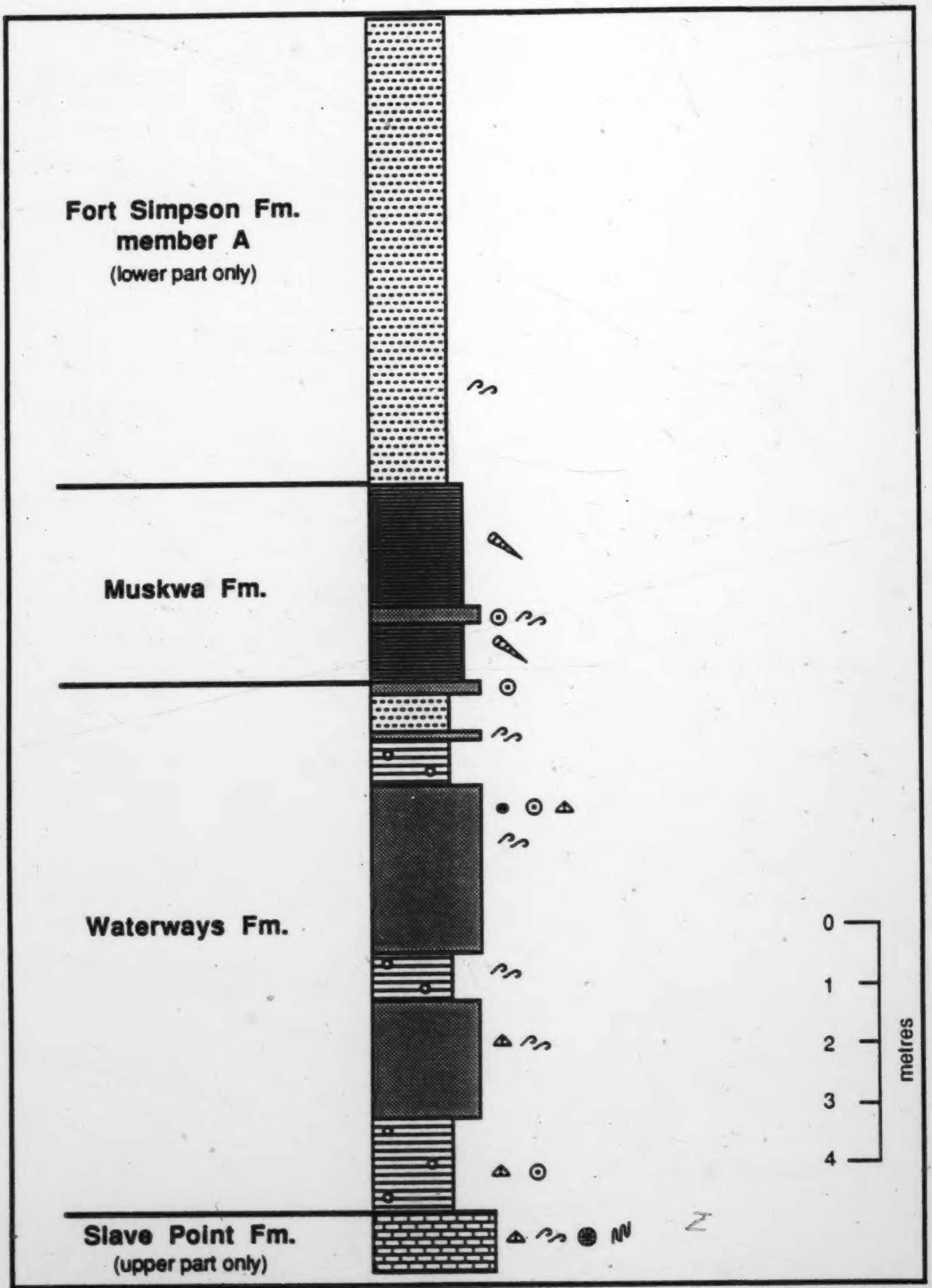


Figure 15. Part of the reference section HW-79-9 showing the Upper Devonian formations overlying the Middle Devonian Slave Point Formation.

The contact between the Slave Point Formation and the overlying Waterways Formation is easily recognizable in core because the limestones of the Slave Point Formation: (1) are commonly cleaner and more indurated than the argillaceous limestones of the Waterways Formation, (2) are commonly stylolitized and bitumen stained, whereas, those of the Waterways Formation are not, (3) generally lack the shale interbeds which are so common in the Waterways Formation, (4) commonly contain a diverse assemblage of corals, stromatoporoids, brachiopods, and less commonly crinoid ossicles whereas limestones and shales of the Waterways Formation contain brachiopods and crinoid ossicles, along with abundant *Styliolina* sp. and ostracodes, and (5) are commonly brown in colour, while limestone beds in the Waterways Formation are usually grey or green grey in colour.

The contact between the Slave Point and Waterways formations is commonly marked by a hardground (Plate 1B). In these cases, dark brown stromatoporoid floatstones and bindstones are overlain sharply by light to medium grey, relatively argillaceous, fossiliferous wackestones to packstones (Plate 1B). The wackestone to packstone unit overlying the hardground surface is usually only 1 to 3 cm thick and is sharply or gradationally overlain by grey, calcareous shales. The presence of the hardgrounds at or near the upper surface of the Slave Point Formation indicates that there was a hiatus, with subsequent erosion and omission, before deposition of the overlying material. Locally, the limestones of the Slave Point Formation are brecciated (Fig. 16).

The contact between the Slave Point and Waterways formations can be easily recognized on gamma-ray-neutron logs. The limestones of the Slave Point Formation have a clean, relatively constant, flat gamma-ray response, indicating a lack of argillaceous material. On all of the geophysical logs examined, a distinctive "kick" on the gamma ray curve occurs at the contact between the Slave Point Formation and the Waterways Formation (Fig. 12). This "kick" correlates with the shaley strata which occur immediately above the Slave Point Formation. Compared to the Slave Point Formation, the gamma-ray profile for the Waterways Formation generally shows: (1) higher gamma counts due to the more argillaceous nature of the

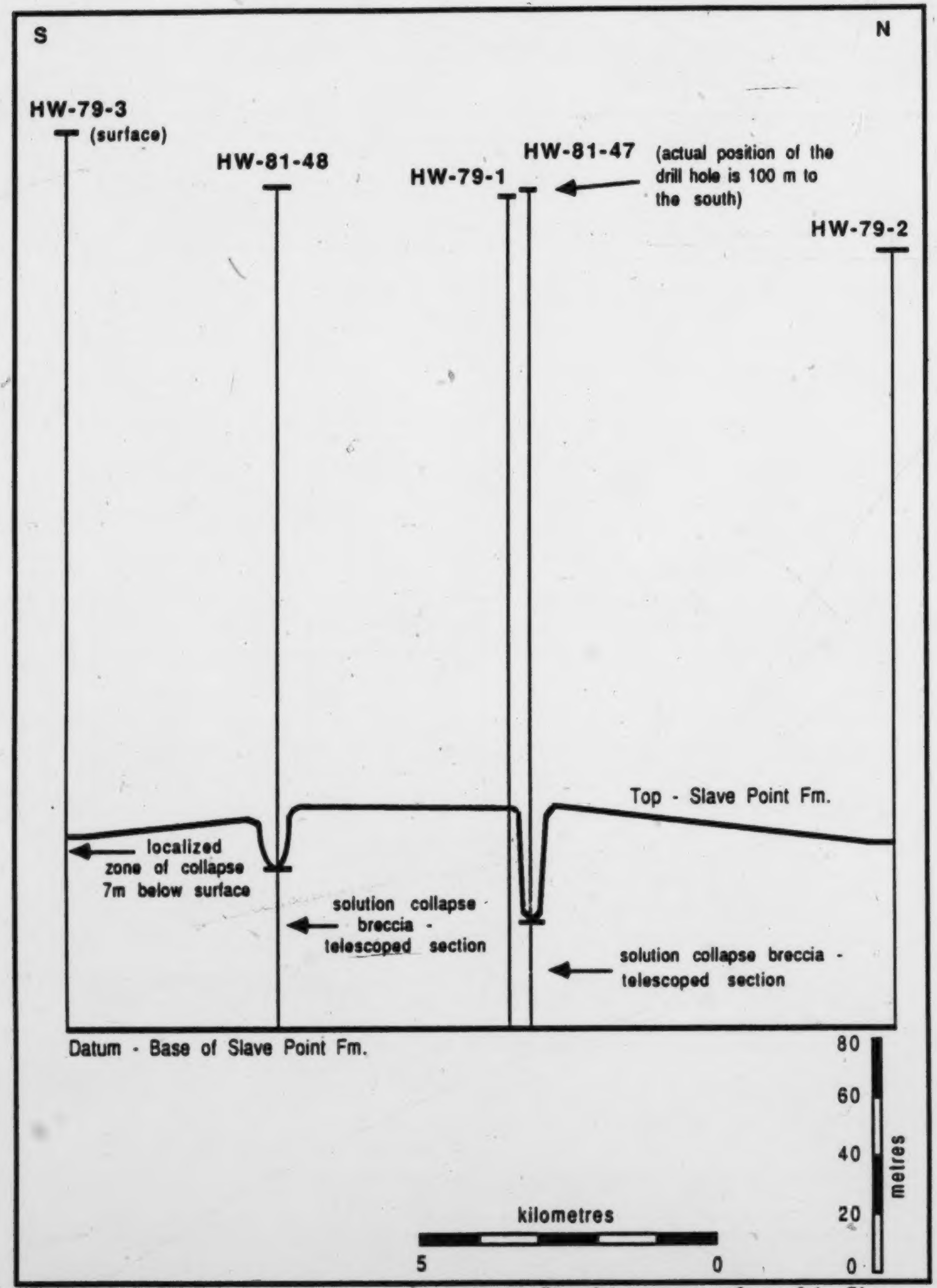

S
N
HW-79-3
(surface)
HW-81-48
HW-79-1
HW-81-47
(actual position of the drill hole is 100 m to the south)
HW-79-2
Top - Slave Point Fm.
localized zone of collapse 7m below surface
solution collapse breccia - telescoped section
solution collapse breccia - telescoped section
Datum - Base of Slave Point Fm.
kilometres
5
0
metres
80
60
40
20
0

Figure 16. Stick section illustrating the irregular profile of the upper surface of the Slave Point Formation in areas affected by sollution collapse (Data supplied by Cominco Ltd.)

limestones, and (2) a more irregular, spikey pattern, due to the presence of numerous interbeds of calcareous shale (Fig. 12).

D. Nature of contact

In the core examined, the contact between the Slave Point Formation and the Waterways Formation ranges from gradational, to sharp but apparently conformable, to sharp with evidence of a hiatus and erosion and omission (Plate 1B). In two holes, HW-79-2 and HW-79-4, the Slave Point Formation is directly overlain by dark brown to black, bituminous, siliceous shales (Figs. 18, 19). Locally, hardgrounds occur at or near the upper surface of the Slave Point Formation (Figs. 18, 19).

In section HW-79-3, the Slave Point Formation is brecciated 7 m below the contact with the overlying Waterways Formation (Fig. 16). The beds above this were not affected by the brecciation event. The breccias commonly consist of angular clasts of dark brown, massive to laminated mudstone, ranging from 0.5 to 20 cm long, which are cemented by coarse, sparry calcite (Plate 1C). The base of the brecciated zone could not be determined.

Examination of data provided by Cominco Ltd. showed that two other sections, HW-81-47 and HW-81-48, in the area adjacent to HW-79-3, contained similar brecciated sequences (Fig. 16). In these sections the entire thickness of the Slave Point Formation is brecciated. Descriptive logs of the core from these holes, by K. M. Carter and D. H. Adams (Cominco Ltd.), indicated that the breccias contain solution residuals, internal sediments, cementation of breccia by coarse, sparry calcite and dolomite, bitumen staining and minor amounts of sphalerite and galena. Brecciation of the limestones in the Slave Point Formation may have resulted from solution collapse associated with a karst landscape (pers. comm. K. M. Carter, 1987).

Brecciation appears to have been a relatively localized feature of the Slave Point Formation. There is no evidence of brecciation in the core from hole HW-79-1, which lies approximately 100 m to the south of HW-81-47 (Fig. 16). The thickness of the Slave Point Formation in HW-81-47 and HW-81-48, has been greatly reduced and telescoped, in comparison to the surrounding drill holes, due to the effects of brecciation. Over a distance of approximately 100 m the thickness of the Slave Point Formation changes from 75 m, in HW-79-1, to 35 m, in HW-81-47 (Fig. 16).

Although brecciation has affected the Slave Point Formation down to the Amco Member at the base of the formation, it has not affected the strata below this. The initiation of solution collapse causing brecciation may have occurred during a brief period of exposure of the upper surface of the Slave Point Formation. However, the main period of brecciation and collapse probably occurred sometime after the deposition of the overlying Upper Devonian shales and carbonates (pers. comm. K. M. Carter, 1987). This assumption is based on the fact that the Upper Devonian strata above the brecciated zones show evidence of plastic deformation and collapse into these features. The exact timing of the brecciation of the Slave Point Formation has not been determined.

The three brecciated intervals in the study area appear to be related to topographic highs on the surface of the Slave Point Formation. If this was initiated during a brief period of exposure, then it is possible that the more structurally elevated portion of the surface of the Slave Point Formation would have been subjected to a greater period of exposure. Similar relationships have been documented for the Presqu'ile dolostones by Rhodes *et al.* (1984). They noted that linear karst trends are associated with depositional "paleo-high ridges" formed at the top of the Pine Point Formation.

It is possible that the karst surface at the top of the Slave Point Formation may be intrastratal in origin, in which case it is not a true paleokarst surface. The fact that the beds overlying the brecciated intervals have slumped into these features indicates solution after burial. In fact, the breccias in the Slave Point Formation show none of the features that have been proposed for the recognition of paleokarst by Wright (1982). Beales and Oldershaw (1969) suggested that the development of karstic breccias in the Presqu'ile dolostones in the Pine Point area may be related to compaction-generated basinal waters. However, Rhodes *et al.* (1984) suggested that the paleokarstification and dolomitization could be related to intermixing of fresh and saline waters at a subsurface interface, below an emergent and subaerially exposed barrier.

E. Lithology

The lithology in the upper part of the Slave Point Formation is not constant and changes from drill hole to drill hole. Recorded lithologies include buff to medium to dark brown, fossiliferous and unfossiliferous mudstones, mudstones with a nodular appearance, highlighted by bituminous "horse tail" seams, bituminous mudstones, fossiliferous wackestones, packstones, and grainstones, and coral-stromatoporoid floatstones, rudstones and locally bindstones. Specimens of *Ladogioides pax* ? were collected from the Slave Point Formation in HW-80-20.

F. Thickness and distribution

The Slave Point Formation is 35 to 75 m thick in the study area. An isopach map (Fig. 13), shows an irregular thickness distribution for the Slave Point Formation. On stratigraphic cross-sections, the top of the Slave Point Formation shows a very gentle topographic relief. Locally, however, this relief is much greater in areas where the Slave Point Formation has been brecciated (Fig. 13). Isopachs indicate a close correspondence between structural highs on the surface of the Slave Point Formation and thin or absent strata of the Waterways Formation (Figs. 13, 17).

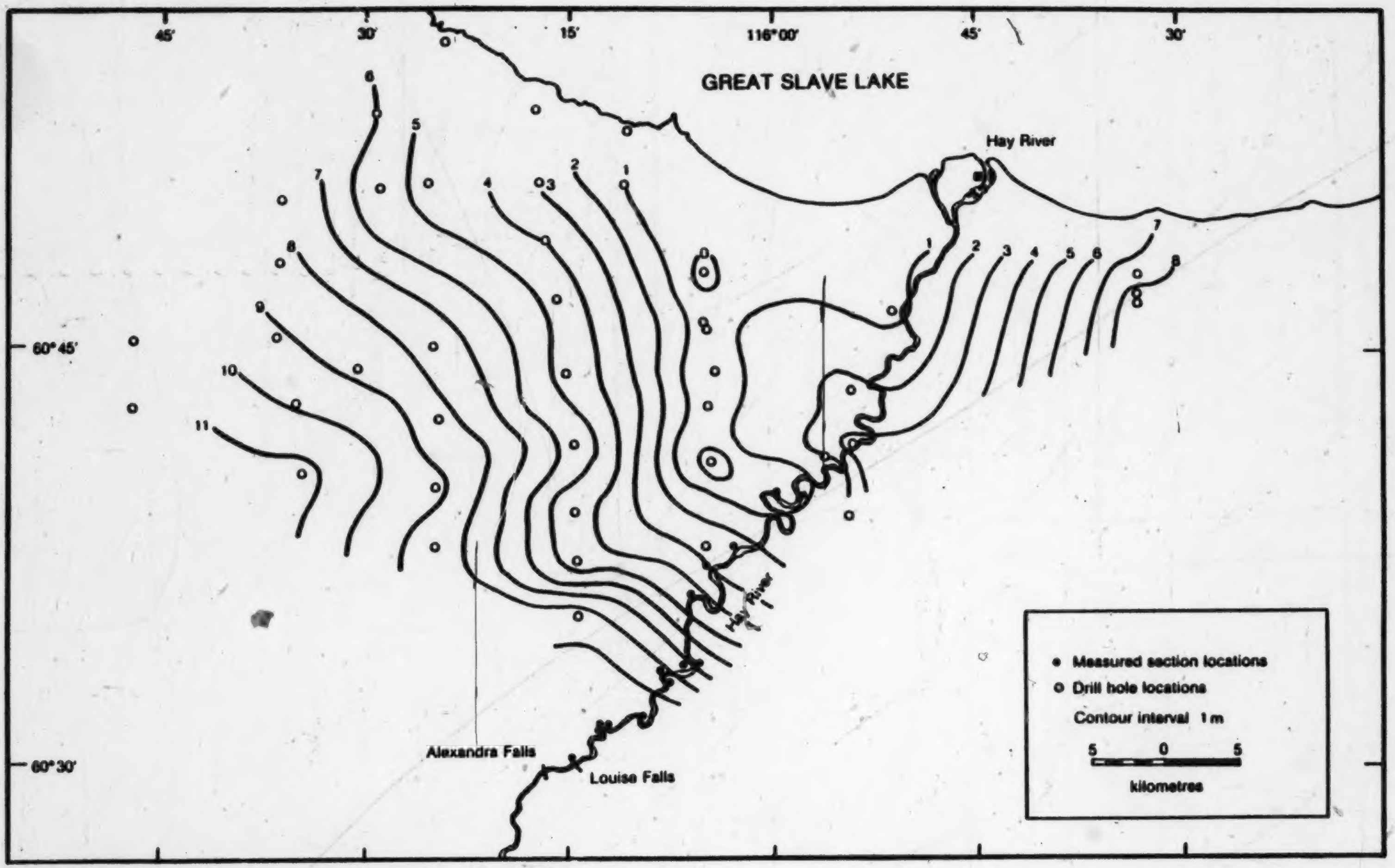


Figure 17. Isopach map of the Waterways Formation.

IV. WATERWAYS FORMATION

A. Introduction

In the reference section HW-79-9 an 8.6 m thick unit of interbedded argillaceous, fossiliferous limestone, including mudstones to packstones, and calcareous green grey shale with limestone nodules (Plate 1D), overlies the Slave Point Formation (Fig. 15). It occurs between the depths of 424 and 415.4 m in HW-79-9. This unit is herein referred to the Waterways Formation. This follows the work of Griffin (1965, 1968) who described a similar lithologic sequence above the Slave Point Formation in the subsurface of northeastern British Columbia, northern Alberta and the southern District of Mackenzie.

B. Upper boundary

The upper boundary of the Waterways Formation is placed at the contact between argillaceous limestone or calcareous shale of the Waterways Formation and the dark brown to black, bituminous, siliceous shales (Figs. 15, 18 to 20; Plate 1D) of the overlying Muskwa Formation. This contact occurs at a depth of 415.4 m in the reference section, HW-79-9.

On gamma-ray-neutron logs, the strata of the Waterways Formation can be recognized by their typical "spikey" profile (due to the interbedded nature of the limestones and shales) and relatively lower gamma and higher neutron counts in comparison to the Slave Point Formation (Fig. 12). The gamma-ray count generally increases toward the top of the Waterways Formation where it is overlain by bituminous shales, which have slightly higher gamma counts.

C. Nature of contact

The contact between the Waterways and Muskwa formations in the reference section and in other cores (Plate 1D), is generally sharp but conformable. Locally, however, the contact is gradational, with green grey, calcareous shales being thinly interbedded with dark bituminous shales.

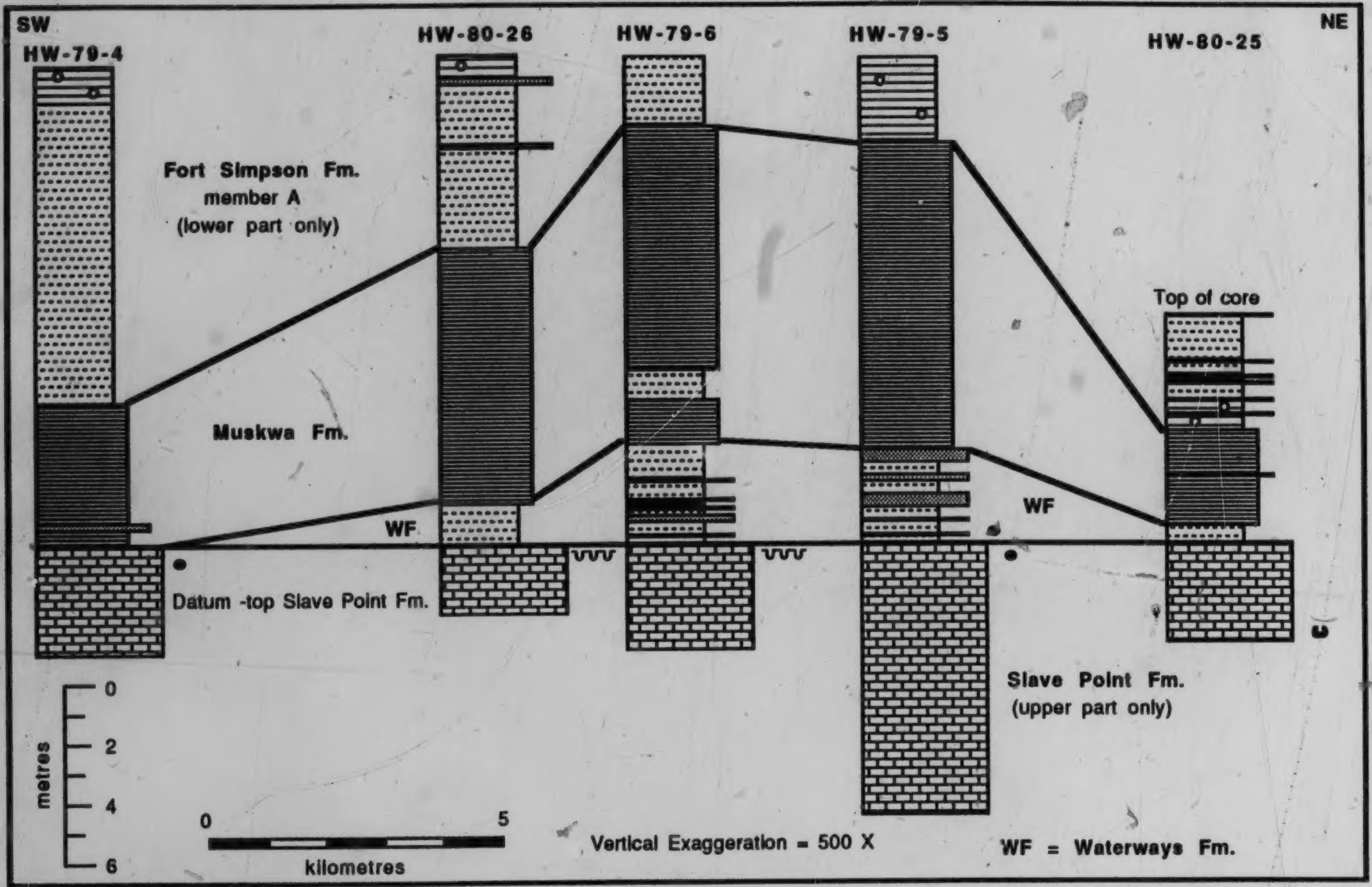


Figure 18. Part of cross section 1 showing correlation of the lowest Upper Devonian strata in the study area and their relation to the underlying Middle Devonian Slave Point Formation.

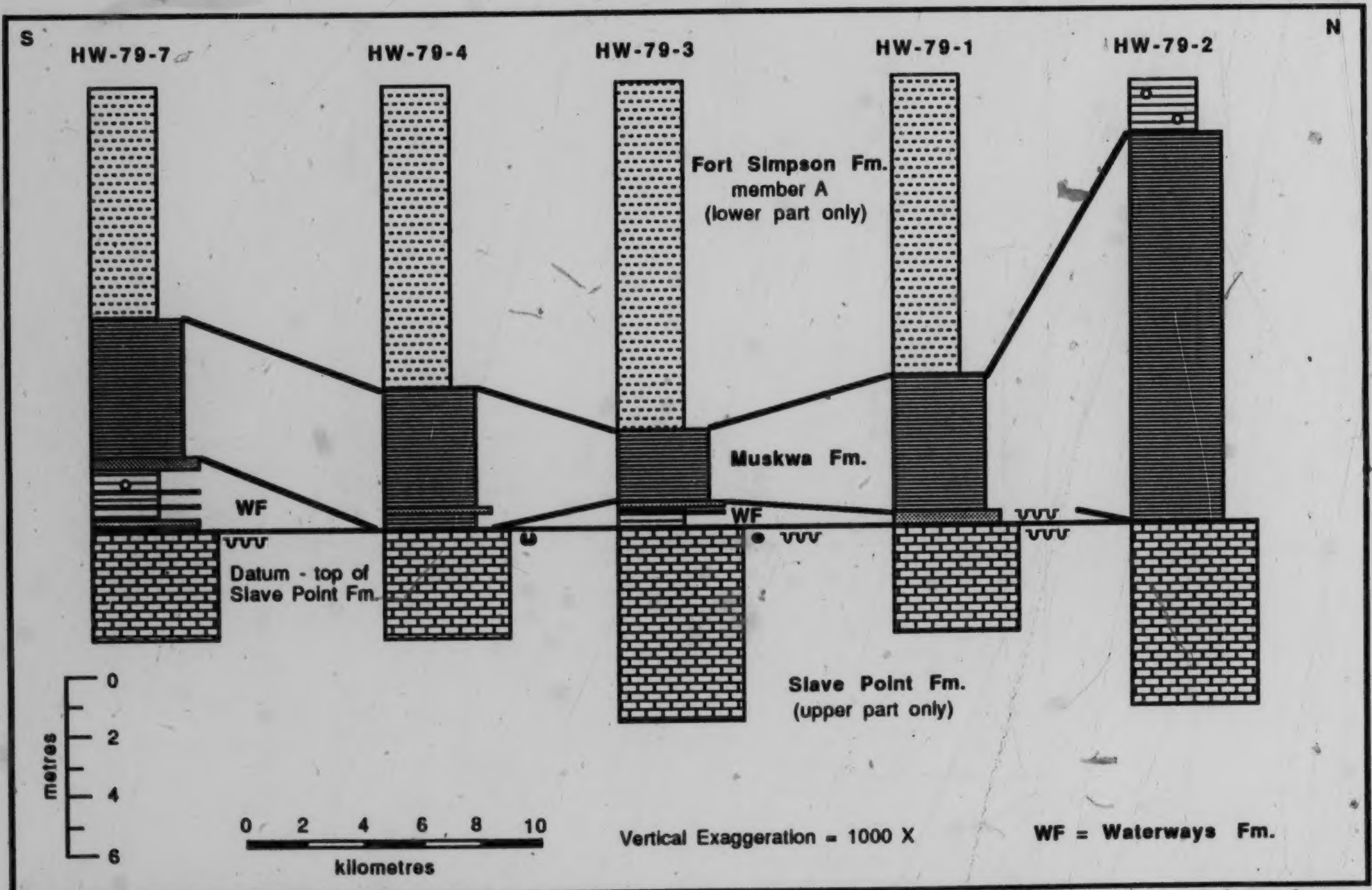


Figure 19. Part of cross section 2 showing correlation of the lowest Upper Devonian strata in the study area and their relation to the underlying Middle Devonian Slave Point Formation.

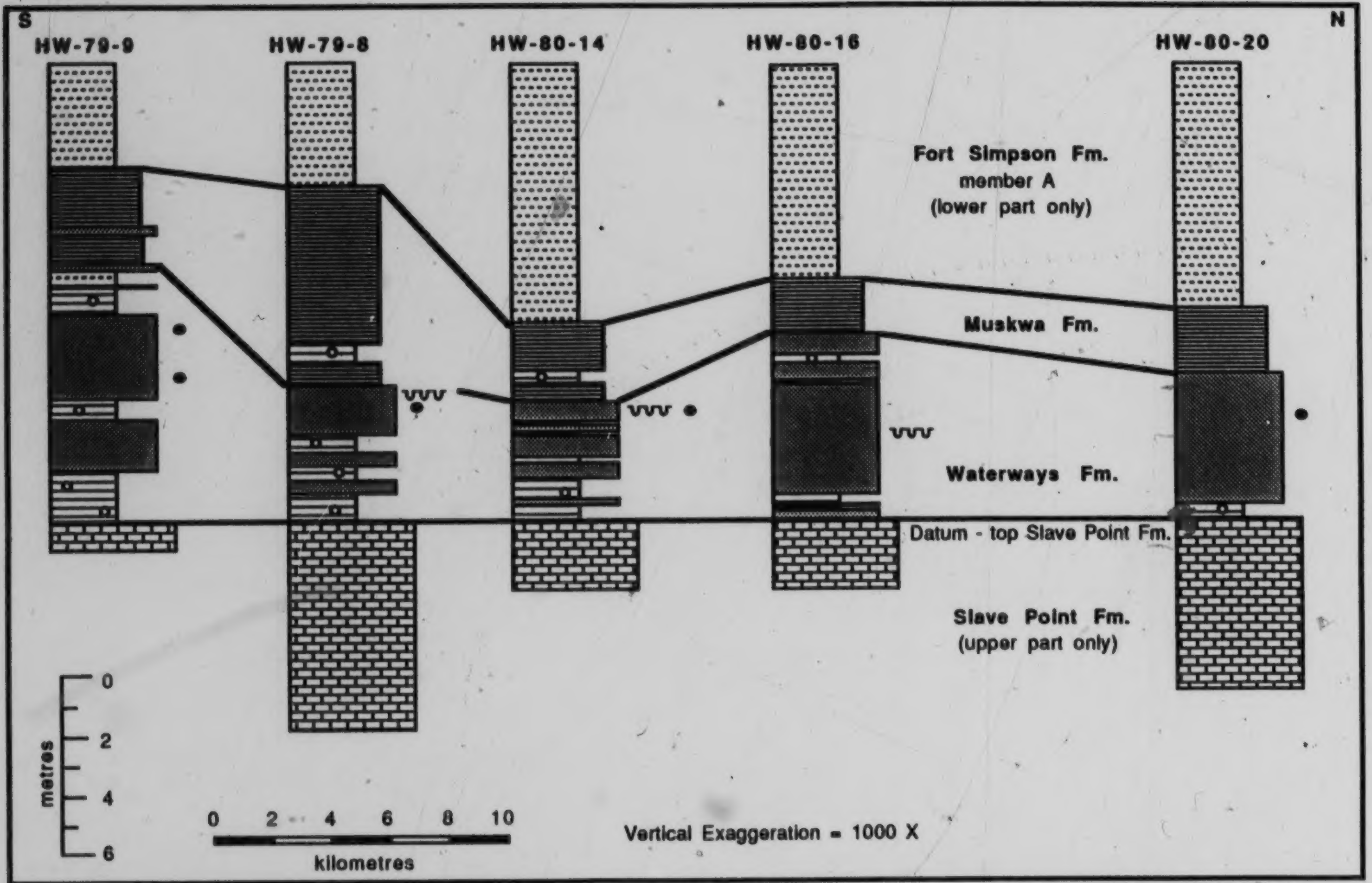


Figure 20. Part of cross section 3 showing correlation of the lowest Upper Devonian strata in the study area and their relation to the underlying Middle Devonian Slave Point Formation.

D. Lithology

Shales in the Waterways Formation are generally green grey to grey green, fissile, and calcareous. They commonly contain abundant argillaceous limestone nodules, which are 0.5 to 10 cm across. Locally the shales contain thin intervals (1 to 10 cm) packed with abraded and disarticulated skeletal material.

The shales are interbedded with green grey to brown grey, argillaceous limestones, ranging from mudstones to packstones (Plate 1E) and, less commonly, grainstones. The limestones commonly have a nodular or mottled appearance due to: (1) the presence of shaley seams around limestone lumps or nodules (Plate 1D), or (2) to the effects of intense bioturbation, which give the rock a mottled appearance (Plate 2A). Well developed hardgrounds are a common feature of many of the limestone beds (Figs. 18 to 21). Limestone beds range in thickness from 1 to 4 m. The contact between the limestone beds and the shale beds is commonly gradational. Both the limestones and the shales contain abundant fossil debris including articulated and disarticulated brachiopods (*Atrypa* sp.), crinoid ossicles, ostracodes and *Styliolina* sp. Small, 0.5 to 1 cm, chitinous linguloid brachiopods are abundant locally. These are similar to the occurrence of *Lingula* cf. *spatulata* Vanuxem in argillaceous limestones of the Firebag Member of the Waterways Formation as noted by Crickmay (1957).

E. Thickness and Distribution

In the study area the Waterways Formation is 0 to 11.2 m thick (Fig. 17). The areas where the Waterways Formation is absent, or thin, appear to correspond to the flanks or crests of topographic highs on the surface of the underlying Slave Point Formation. However, this is not always the case; at HW-79-1 and HW-79-3, a thin (0.4 to 0.6 m) unit of Waterways Formation is present. The Waterways Formation tends to thicken away from topographic highs.

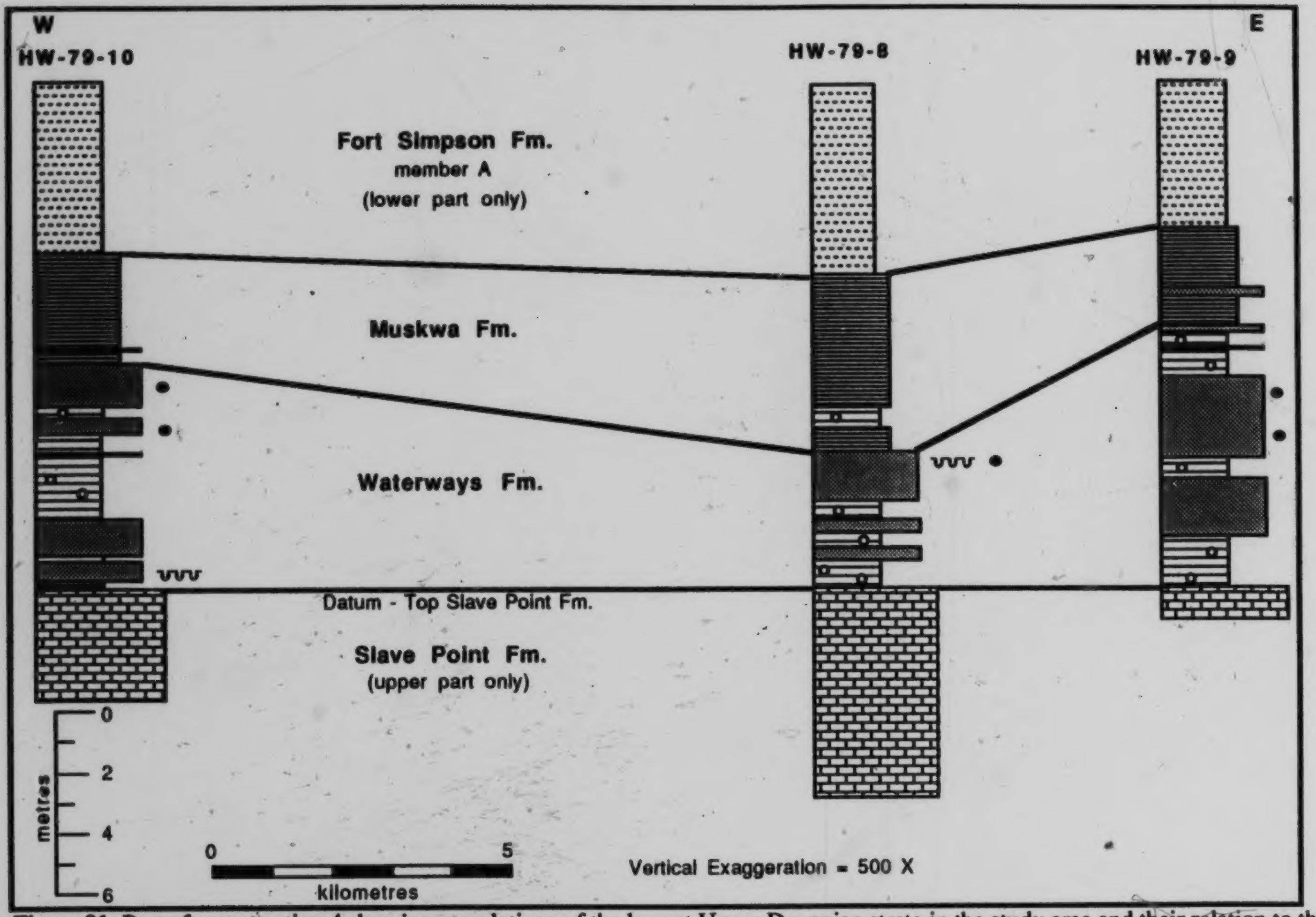


Figure 21. Part of cross section 4 showing correlations of the lowest Upper Devonian strata in the study area and their relation to the underlying Middle Devonian Slave Point Formation.

V. MUSKWA FORMATION

A. Introduction

In the reference section HW-79-9 the 3.3 m of dark brown to black, bituminous, siliceous shales (Plate 2B) overlying the Waterways Formation are herein assigned to the Muskwa Formation (Fig. 15). It occurs between the depths of 415.4 and 411.8 m in the reference section. Where the Waterways Formation is absent these dark shales directly overlie the Slave Point Formation (Figs. 18, 19). In the reference section, the Muskwa Formation is overlain by calcareous, green grey shales of the Fort Simpson Formation (Fig. 15).

The use of the term Muskwa Formation for this unit follows the usage of Griffin (1965, 1968). This unit was recognized to the west of the study area by Belyea and McLaren (1962, Fig. 3), but was informally referred to as the "black shale member" of the Hay River Formation. The exact use of the term, was not defined. Williams (1977, Figs. 12, 13) suggested that the Muskwa Formation overlies the Waterways Formation west of approximately 119° W longitude. He noted that, to the east of this area, the Waterways and Muskwa formations could not be subdivided due to interbedding of the two units. He suggested that the radioactivity of the Muskwa Formation decreases from west to east and that east of about 117° W longitude, there are no radioactive markers within, or above, the Waterways Formation. The sections examined in this study indicate that this is not the case. The radioactivity of the Muskwa Formation does decrease but, the lithologies of the two formations are not interbedded, except locally at the contact between the two.

B. Upper boundary

In the reference section HW-79-9 the upper boundary of the Muskwa Formation is placed at the contact between dark brown, bituminous shales and green grey, calcareous, fissile shales of the overlying Fort Simpson Formation (Fig. 15). This contact occurs at a depth of 411.8 m in the reference hole.

On gamma-ray-neutron logs the Muskwa Formation is difficult to recognize because it is relatively thin and appears to be less radioactive than the Muskwa Formation developed farther to the southwest. This may be part of the reason why the Muskwa Formation has not been previously recognized in this area.

By carefully comparing drill cores with geophysical logs, it was possible to recognize a "kick" on the gamma-ray profile which corresponds to the Muskwa Formation (Fig. 12). The black shales of the Muskwa Formation have only slightly higher gamma counts than the shales of the overlying and underlying formations.

This unit is readily recognizable in drill core and retains a lithologic composition closely comparable to the strata mapped as Muskwa Formation in the subsurface of northeastern British Columbia by Griffin (1965, 1968). Therefore, it is proposed herein that this unit should be recognized as a distinctive formation. It should be referred to the Muskwa Formation and removed from strata previously assigned to the Hay River Formation by Belyea and McLaren (1962).

C. Nature of contact

The upper and lower contacts of the Muskwa Formation are generally gradational; however, locally the contact is sharp (Plate 3A). This gradation is represented by a thin section of interbedded greenish grey, calcareous and dark brown, siliceous shale. However, where the Muskwa Formation overlies limestone of the Slave Point Formation the contact is sharp.

D. Lithology

The Muskwa Formation generally consists of dark brown to black, laminated to fissile, siliceous, bituminous shale. The shales have a strong odour of bitumen when broken open. Although generally very hard, they are commonly fissile. Pyrite is ubiquitous, occurring as isolated nodules (up to 2 to 3 cm in length), consisting of very fine crystals or, as 1 to 3 cm thick beds in the shales (Plate 1D, 2B).

The noncalcareous shales commonly contain fine calcite grains which give the shale a distinctive speckled appearance (Plate 2B). These grains, between 0.05 and 0.1 mm in size, are cone shaped to tapered in appearance, with smooth exteriors or rare transverse striae and smooth interior wall surfaces. The tapered end of the cones are commonly slightly bulbous. These are most likely shells of *Styliolina* sp. These are commonly concentrated in 1 to 10 cm thick intervals in the shales (Plate 1D). Small, 0.5 to 1 cm, chitino-phosphatic*Lingula* sp. occur locally, packed in thin zones in the shales.

Locally, the dark bituminous shales are thinly interbedded with grey, calcareous or noncalcareous shales. Rarely, 1 to 10 cm thick beds of variably fossiliferous, argillaceous mudstone to packstone and 1 to 5 cm, dark brown to black, bituminous, unfossiliferous mudstones are present as interbeds in the dark shales of the Muskwa Formation. These beds are difficult to distinguish from the siliceous, bituminous shale, except that they react with acid.

E. Thickness and Distribution

In the study area the Muskwa Formation is 1 to 13 m thick (Fig. 22). By comparison, Griffin (1965) reported thicknesses of between 15 m (50 ft) and 30 m (100 ft) and, locally, 45 m (150 ft) to 76 m (250 ft), for the Muskwa Formation in northeastern British Columbia. To the southwest of the study area, Williams (1977, Fig. 13) noted that the Muskwa Formation is 32.6 m thick in the Fina Gulf Trainor Lake B-24 well (60° 03' N; 119° 49'W).

The underlying topography on the top of the Waterways Formation and, locally, where the Waterways Formation is absent, the Slave Point Formation appears to have had a subtle effect on the distribution and thickness of the Muskwa Formation (Figs. 8 to 12). The thinnest sections of the Muskwa Formation show a close correlation with the thinnest sections of the underlying Waterways Formation. The irregular relief on the surface of the Slave Point Formation may have affected the deposition of both the Waterways and Muskwa formations.

The presence of the Muskwa Formation immediately overlying the Slave Point Formation might indicate that the Waterways Formation was eroded locally before deposition of the overlying Muskwa Formation. No physical evidence of erosion was detected in the cores examined; however, the local occurrence of hardgrounds in the Waterways Formation

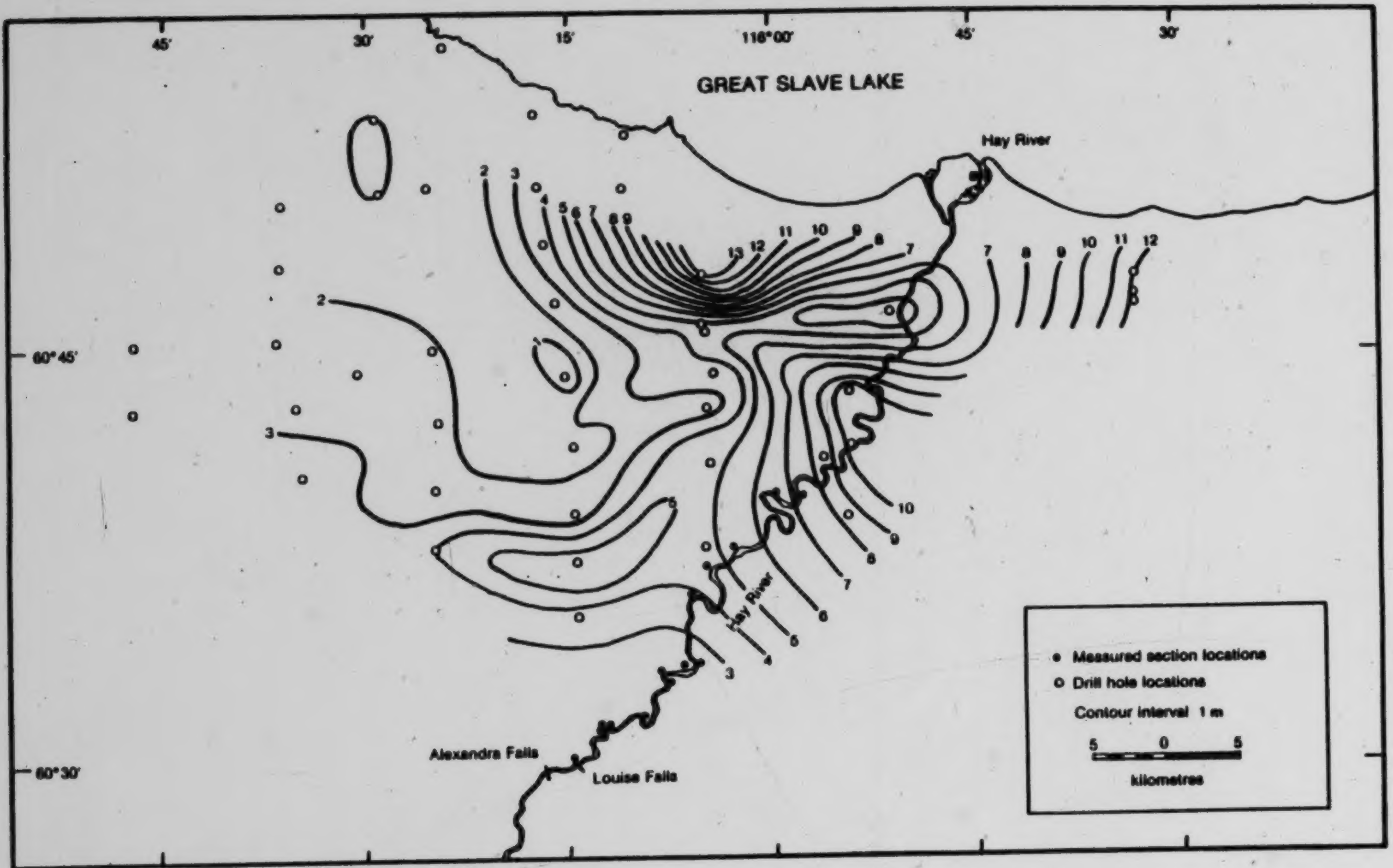


Figure 22. Isopach map of the Muskwa Formation.

indicate hiatuses with periods of erosion and omission. It is also possible, however, that the Waterways Formation was not deposited in some areas because of the effects of the underlying topography on the Slave Point Formation. Isopach maps of the Slave Point, Waterways and Muskwa formations indicate a fairly close correspondence between topographic highs (indicated by localized thicks on the isopach map) on the surface of the Slave Point Formation and thinning or absence of the Waterways Formation (Figs. 13, 17, 22).

A similar relationship between the Slave Point, Waterways and Muskwa formations was noted by Griffin (1965). He suggested that there was considerable erosion of the Slave Point Formation and the overlying Beaverhill Lake Formation (=Waterways Formation) before deposition of the Muskwa Formation. Williams (1977) suggested, on the basis of well log correlations, that there was no evidence of an erosional unconformity at the base of the Muskwa Formation, in the area south of Great Slave Lake. Instead he interpreted from logs, an interbedding of the Waterways and Muskwa formations in this area and suggested that this was evidence against an unconformity.

VI. FORT SIMPSON FORMATION

A. Introduction

In the reference section HW-79-9, the 292.3 m (411.8 to 120.1 m) of green grey, calcareous shale containing minor amounts of argillaceous, variably bioclastic limestone, quartzose limestone and calcareous siltstone, overlying dark bituminous shale of the Muskwa Formation and underlying interbedded limestones and calcareous shale of the Escarpment Formation, is herein referred to the Fort Simpson Formation (Fig. 23). The assignment of these strata to the Fort Simpson Formation follows the work of Crickmay (1953, 1957) and House and Pedder (1963). The only difference being that these workers did not recognize the Waterways and Muskwa formations at the base of the Fort Simpson Formation. The Fort Simpson Formation is exposed locally along Hay River (Plates 2, 4) and is completely represented in drill core (Plates 2 to 5).

Previously, the Waterways, Muskwa and Fort Simpson formations, recognized in this study, had been included as one unit (Fig. 4) and referred to the lower member (Belyea and McLaren, 1962) or member A (Jamieson, 1968) of the Hay River Formation. After examing this section in drill core it became obvious that: (1) the calcareous shales lying above the Muskwa Formation and below interbedded limestones and shales, previously assigned to the Escarpment Member of the Hay River Formation, closely resemble the Fort Simpson Formation as described by Belyea and McLaren (1962), and (2) this thick package of calcareous shale is distinctly different from the overlying strata previously referred to the Escarpment Member of the Hay River Formation and should, therefore, be considered a separate formation.

In the reference section HW-79-9 the Fort Simpson Formation can be subdivided, on the basis of lithology, into four informal members, A to D (Fig. 23). These are recognizable, in core and on geophysical logs, throughout the study area (Figs. 8 to 12).

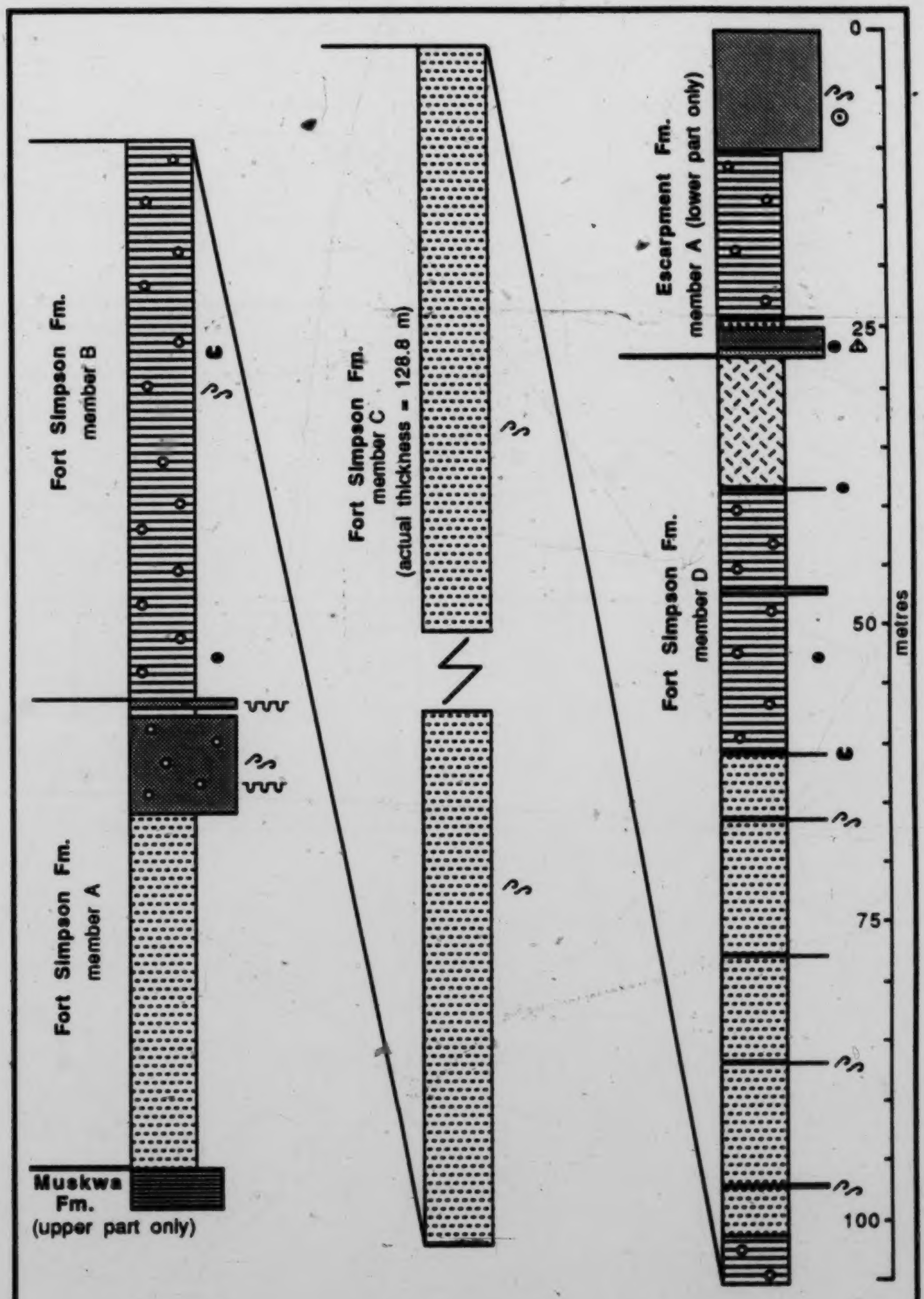


Figure 23. Part of the reference section HW-79-9 showing divisions of the Fort Simpson Formation and lower and upper contacts with the Muskwa and Escarpment formations, respectively.

B. Upper boundary

In the reference section, the upper boundary of the Fort Simpson Formation is placed at the contact between silty, green grey, calcareous shale of the Fort Simpson Formation and the base of a 0.5 m thick, green grey, intensely bioturbated, calcareous to dolomitic, quartzose siltstone at the base of the Escarpment Formation (Fig. 23). This contact occurs at a depth of 120.1 m in the reference section HW-79-9. It also occurs in the core from HW-79-8, HW-79-10, and HW-80-14. The lithology of the Fort Simpson Formation at the contact is variable throughout the study area. Shales at the top of the formation range from silty, mottled maroon and grey shale, and green grey, calcareous shale, to green grey, calcareous shale with limestone nodules.

The upper boundary of the Fort Simpson Formation is exposed in sections HR-101, HR-102, HR-111, and HR-103 along Hay River, downstream from Louise Falls. In those sections the upper boundary of the Fort Simpson Formation was placed at the contact between green grey, silty shales of the Fort Simpson Formation and the base of a distinctive, resistant, rubbly weathering, 2.0 to 3.8 m thick, limestone bed (Plate 5D). Locally, at the base of this limestone bed, a 0.1 to 0.3 m thick, rippled, calcareous siltstone to quartzose limestone bed occurs (Plate 5B). At these locations the upper boundary of the Fort Simpson Formation is placed at the base of this bed. The rippled bed is well exposed at sections HR-111 and HR-103 at 4.5 and 1.5 m above river level, respectively.

The distinctive rubbly weathering limestone (Plate 5E) at the base of the Escarpment Formation contains an abundant brachiopod fauna, numerous solitary and colonial corals and lesser numbers of gastropods and goniatites. Based upon the published descriptions, it is assumed that this is the same as the "*Schizophoria* bed" described by Belyea and McLaren (1962) at the base of their Escarpment Member of the Hay River Formation and the limestone bed described by Jamieson (1968) at the base of her member B of the Hay River Formation.

On geophysical logs the upper boundary of the Fort Simpson Formation is picked at the base of a relatively prominent, low gamma count "kick". This "kick" corresponds to the limestone bed at the base of the Escarpment Formation as determined by matching the geophysical logs to drill core. The Fort Simpson Formation is characterized by relatively flat gamma-ray and neutron log profiles (Fig. 12). The gamma count is generally high due to the large proportion of shale in the formation. Locally, the gamma count is reduced by the presence of very calcareous shales grading to very argillaceous mudrock or, by the presence of thin limestone beds in the shale. In these parts of the section there is a decrease in the gamma and increase in the neutron counts.

C. Nature of contact

In the reference section HW-79-9 the contact between the Fort Simpson Formation and the overlying Escarpment Formation is irregular to slightly gradational. There is a slight interfingering of the two lithologies at this contact due to the effects of bioturbation (Plate 5C). Cylindrical, subvertical burrows of *Teichichnus* sp. extend from the calcareous sandstone at the base of the Escarpment Formation, 1 to 2 cm downward into argillaceous siltstone to silty shale of the Fort Simpson Formation (Plate 5C). The calcareous sandstones above the contact contain *Planolites* sp. (Plate 5C)

In diamond drill core and measured sections in the rest of the study area this contact is generally sharp. In these cases, such as at HR-102 (Plate 5D), HR-103 and HR-111, the silty shales of the Fort Simpson Formation are sharply overlain by quartzose siltstone and/or limestone at the base of the Escarpment Formation.

D. Lithology

The Fort Simpson Formation (Fig. 23) consists primarily of green grey, fissile, calcareous shale and calcareous shale with limestone nodules. In outcrop, the shales weather recessively and form soft, slump covered slopes (Plates 2C, 2D). Commonly, these shales grade into rocks which have a composition between very calcareous mudrock and very argillaceous limestone. These are difficult to recognize and are generally indistinguishable from the calcareous shales except that they are less fissile and more indurated (Plate 3D).

Lesser amounts of noncalcareous, grey to black shale (Plate 3E), silty shale, and maroon and green grey mottled shale occur locally in the formation (Fig. 23). Thin beds of limestone commonly occur near the bottom and to a lesser degree, the top of the Fort Simpson Formation. They are variably fossiliferous and argillaceous and commonly have a mottled appearance. Toward the top of the Formation the number of thin limestone beds decreases and the number of thin, calcareous, quartzose siltstone to fine sandstone beds increases. A well developed hardground occurs near the top of the member in the section exposed at HR-101 (Plate 2D).

Based on the descriptive lithologic logs of the Fort Simpson Formation by Belyea and McLaren (1962) in the Briggs Lake Turkey No. 1 (type section of the Fort Simpson Formation), Briggs Rabbit Lake No. 1, and Briggs Foetus Lake No. 1 wells, it is evident that the amount of limestone in the shales decreases toward the west. In this direction the amount of calcareous quartzose sandstone and siltstone in the formation increases at the expense of limestone. The descriptions of the Fort Simpson Formation from these sections closely resembles the lithology of the Fort Simpson Formation as determined in this study.

E. Thickness and distribution

In the reference section the Fort Simpson Formation is 292.3 m thick (Fig. 5). In the study area the formation is 275.8 to 292.3 m thick. In general, the formation retains a relatively uniform thickness throughout the study area. Local, remnant topographic irregularities on the top of the Muskwa Formation appear to have had a minor effect on the thickness of the Fort Simpson Formation since it tends to thin slightly in areas underlain by relatively thick sections of the Slave Point, Waterways and Muskwa formations (Fig. 12).

Farther to the west, outside of the study area, the Fort Simpson Formation thickens. In the type section, in Briggs Turkey Lake No. 1 well, the Fort Simpson Formation is 591 m (1,940 ft) thick and is overlain by silty, fossiliferous limestones of the Jean-Marie Member of the Redknife Formation (Belyea and McLaren, 1962).

On the basis of lithology the Fort Simpson Formation can be subdivided into 4 informal members, A to D.

F. Member A

Introduction

In the reference section HW-79-9 the basal 39.1 m (411.8 to 372.5 m) of calcareous green grey shale, with a number of argillaceous limestone beds (Plate 3B) near the top, is herein informally referred to member A of the Fort Simpson Formation (Fig. 23).

Upper boundary

The upper boundary of member A, which is placed at the contact between nodular, fossiliferous wackestone and green grey calcareous shale, with scattered, argillaceous limestone nodules, of the overlying member occurs at a depth of 372.5 m in the reference section.

On gamma-ray-neutron logs member A can be recognized by its relatively high gamma count, flat profile and flat neutron response (Fig. 12). The upper boundary of the member on geophysical logs is placed at the top of a distinctive low gamma and high neutron count "kick" which corresponds to the limestone unit at the top of the member (Fig. 12). The log profiles for these units are roughly equivalent to the response of the limestones in the Waterways Formation. As a result of their distinctive log profiles the limestones at the top of member A provide a useful marker which can be traced throughout the study area. Locally, however, the limestone units grade into shale (Fig. 12), in a basinward direction.

After examination of the geophysical logs used by Williams (1977), it became apparent that this log marker could be recognized in areas to the south and west of the study area. Thus, using these logs the member can be traced into the area south of Tathlina Lake near the Northwest Territories - Alberta border (Williams,1977; Figure 12 - Pan Am Andex C-1 Cameron C-22, 60° 20' N, 117° 45' W @ 1183 m; H. B. Beatty Lake 10-28-126-1W6 @ 1143 m; H. B. Beatty Lake 2-16-126-1W6 @ 1192 m) and south into northern Alberta near Peace River (Williams, 1977; Figure 9 - Texaco Whitesand 5-35-126-12W5 @ 399 m; Texaco Whitesand 13-21-124-11W5, @ 443 m; Shell Yates *et al.* Yates 7-25-120-10W5, @ 916 m; Pan Am B-1 Two Lakes 2-10-118-8W5 @ 926 m). Williams (1977) included this unit in the

Waterways Formation. However, he did not recognize the underlying Muskwa Formation.

Nature of contact

In the reference section the contact between nodular mudstone to wackestone at the top of member A and calcareous shale with limestone nodules of member B is relatively sharp. The nature of the contact changes throughout the study area. Locally, the contact is gradational with nodular limestones grading into calcareous shale with numerous nodules, and into calcareous shale with relatively fewer nodules, floating in a shale matrix. In this case the contact is placed at the highest occurrence of indurated nodular limestone.

Lithology

In the reference section, member A consists of green grey calcareous, fissile shale with some interbeds of argillaceous limestone. Locally, thin zones containing abundant disarticulated skeletal material, mainly brachiopods (*Nervostrophia* sp.) and crinoid ossicles, are common. Brachiopods collected from shales and carbonates in the member include *Nervostrophia* sp., *Calvinaria* sp., *Ladogioides* sp., *Montelasmina besti*?Pedder, *Cyrtospirifer thalattodoxa* Crickmay, *Nervostrophia vestita* Crickmay, and *Schizophoria* sp. (written comm., B. Jones, 1986).

A number of argillaceous, nodular to intensely bioturbated, fossiliferous limestone beds (0.1 m to 8.2 m) occur at the top of the member (Figs. 24 to 27). In the rest of the study area these beds range from 0.05 to 9 m in thickness. The limestones commonly consist of mudstone to wackestone and locally packstone (Plate 2E) which contain abundant abraded brachiopod, crinoid ossicle and ostracod fragments (0.5 to 1.0 mm long). In core the limestones are commonly characterized by their distinctive nodular appearance (Plate 3B). Light grey, argillaceous limestone nodules, 1 to 20 cm across, generally with sharp, irregular boundaries, are locally surrounded by wispy, dark grey green, argillaceous mudstone to calcareous shale seams (Plate 2F). The only difference between the nodules and the surrounding matrix is that the matrix contains more argillaceous material. The nodules and matrix commonly consist of cryptocrystalline calcite. The nodules are commonly fractured

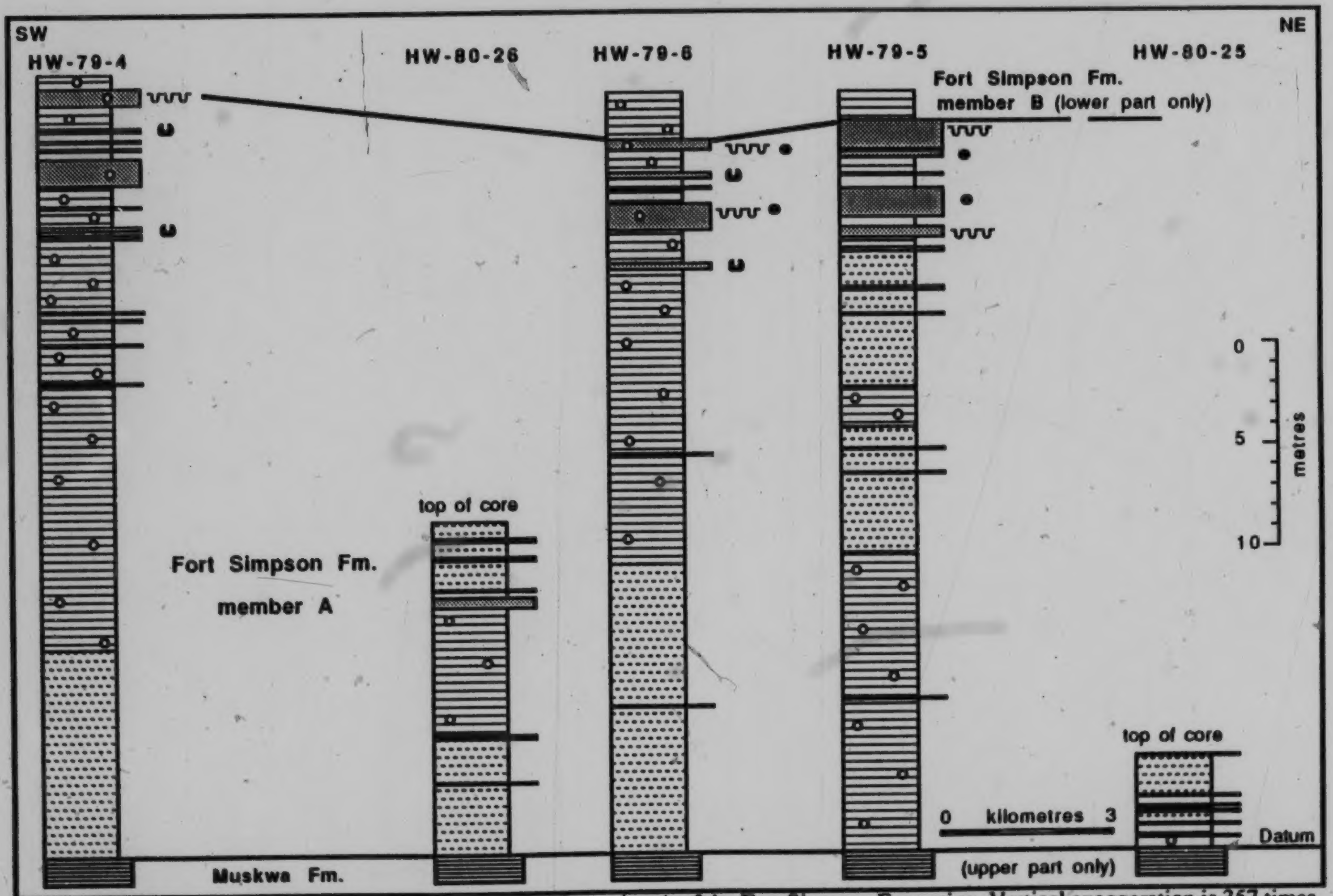


Figure 24. Part of cross section 1 showing correlations of member A of the Fort Simpson Formation. Vertical exaggeration is 357 times.

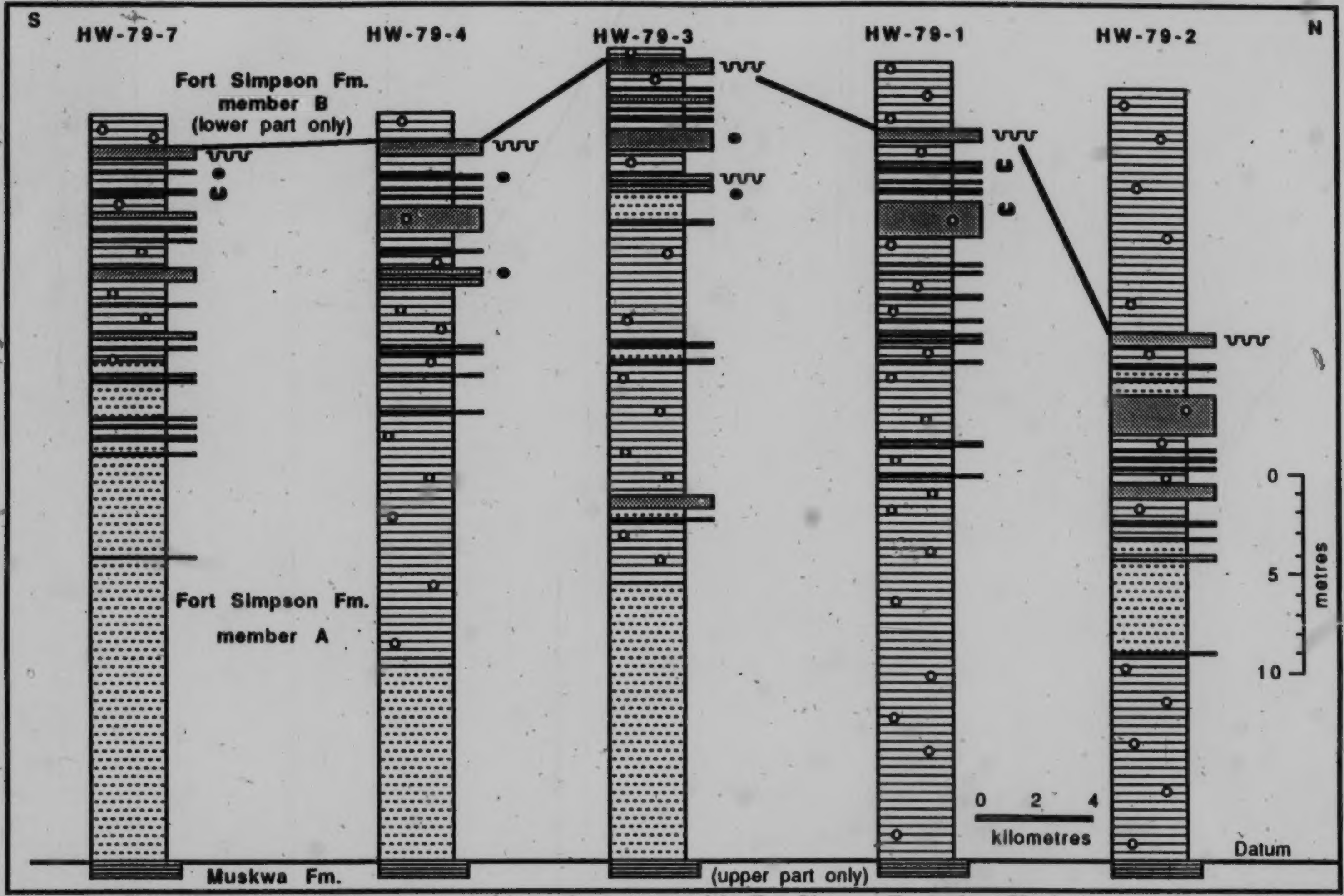


Figure 25. Part of cross section 2 showing correlations of member A of the Fort Simpson Formation. Vertical exaggeration is 666 times.

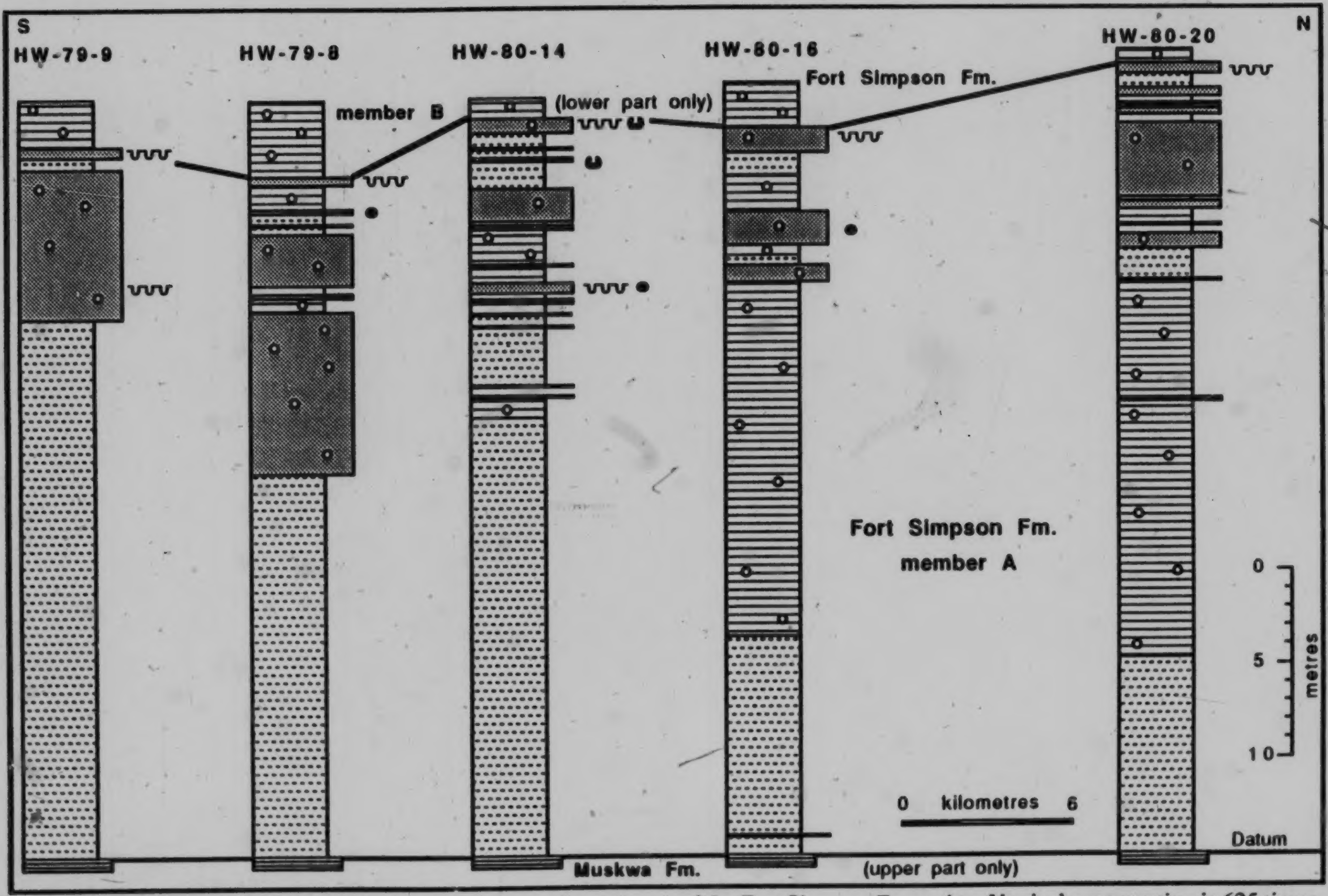


Figure 26. Part of cross section 3 showing correlations of member A of the Fort Simpson Formation. Vertical exaggeration is 625 times.

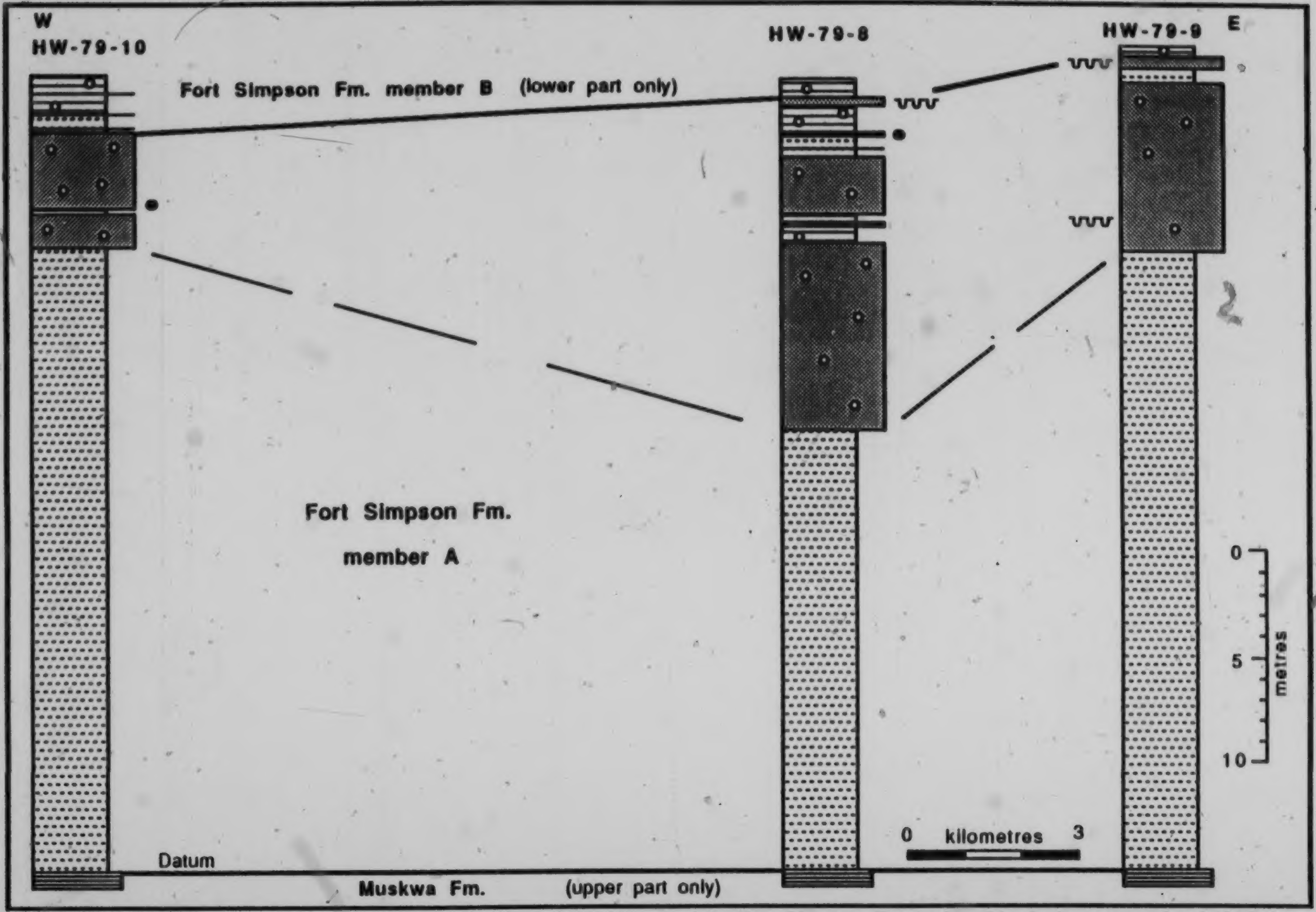


Figure 27. Part of cross section 4 showing correlations of member A of the Fort Simpson Formation. Vertical exaggeration is 357 times.

(Plate 2F) whereas the surrounding argillaceous matrix is not. The fractures are commonly filled by cryptocrystalline and in some cases, sparry calcite. Locally, the nodules represent the lithified fills of burrows preserved in full relief (Plate 4A). A unique feature of these limestone beds are the hardgrounds (Figs. 24 to 27; Plate 2E) which can be traced throughout most of the study area.

Thickness and Distribution

In the reference section HW-79-9, member A of the Fort Simpson Formation is 39.1 m (411.8 to 372.5 m) thick (Fig. 5). In the surrounding area the member ranges from approximately 27 to 42 m in thickness (Fig. 28). The member is thickest in the central part of the study area in the vicinity of HW-80-20, HW-79-3, and HW-79-8 (Fig. 28). In general, the thickness of the formation is relatively uniform and appears to parallel the slight topographic relief of the underlying Muskwa Formation. Locally, it appears that the thickness distribution of the underlying Upper Devonian strata affected the deposition of member A (Fig. 12). From north to south the Waterways and Muskwa formations increase slightly in thickness while member A of the Fort Simpson Formation decreases in thickness (Fig. 12).

G. Member B

Introduction

In the reference section the 46.7 m of calcareous green to grey shale with limestone nodules and some thin limestone beds, overlying the limestone at the top of member A and underlying calcareous shales of member C, are herein informally referred to member B of the Fort Simpson Formation. In the reference section member B occurs between the depths of 372.5 and 327.5 m. Member B is distinctive in drill core due to the ubiquitous presence of argillaceous limestone nodules (Plate 3C) and, locally, 1 to 10 cm thick limestone beds in the shale.

Upper boundary

In the reference section the upper boundary of member B, which occurs at a depth of 327.5 m, is placed at the contact between calcareous shale containing argillaceous limestone

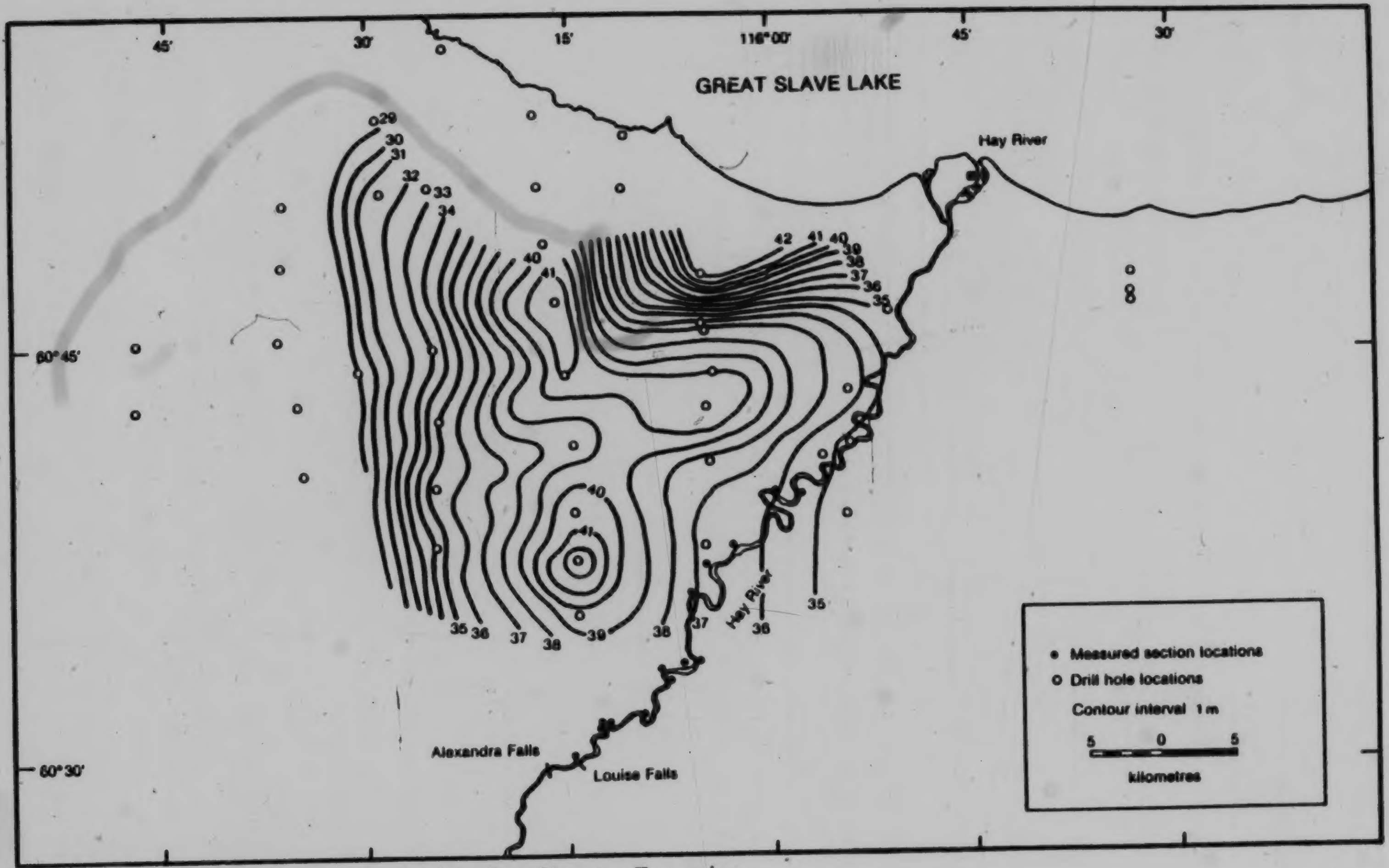


Figure 28. Isopach map of member A of the Fort Simpson Formation.

nodules and green grey calcareous shales without nodules, of the overlying member (Fig. 23). The placement of this boundary is somewhat arbitrary since the contact is is not sharply defined. The contact is picked at the highest occurrence of limestone nodules in the calcareous shale of member B. The upper boundary of member B maintains a relatively constant stratigraphic level throughout the study area (Figs. 8 to 12).

In many of the cores (e.g. HW-80-14, HW-80-16, HW-80-20) the upper boundary of member B was placed at the top of the uppermost limestone bed (10 cm thick) in the shales of member B (Figs. 29 to 31). These beds also maintain a relatively constant stratigraphic level throughout the study area (Figs. 29 to 31).

On geophysical logs the contact between member B and member C is difficult to recognize. However, after comparing geophysical logs to the corresponding drill core this contact could be placed immediately above a slight inflection on the gamma-ray profile to relatively higher API values in the overlying calcareous shales of member C (Fig. 12). There is a corresponding decrease in the neutron count at this point. The inflection in the gamma-ray profile may be due to either the presence of a thin limestone bed at the top of member B or, the change from shale with limestone nodules to shale without nodules.

Member B is characterized on the logs by a relatively consistent, high gamma count, in comparison to that of member A (Fig. 12). Thin limestone beds in the shale are represented by low gamma "kicks" and stand out in relief in comparison to the flat response of the shale. The neutron response generally shows a consistently flat profile (Fig. 12).

Nature of contact

The nature of the contact between members B and C of the Fort Simpson Formation changes throughout the study area. In general, the contact is gradational. In sections on the southern margin of the study area (Fig. 32), this gradation is represented by a change in lithology from calcareous shale with argillaceous limestone nodules to calcareous shales without nodules. Toward the north the number of thin limestone beds increases.

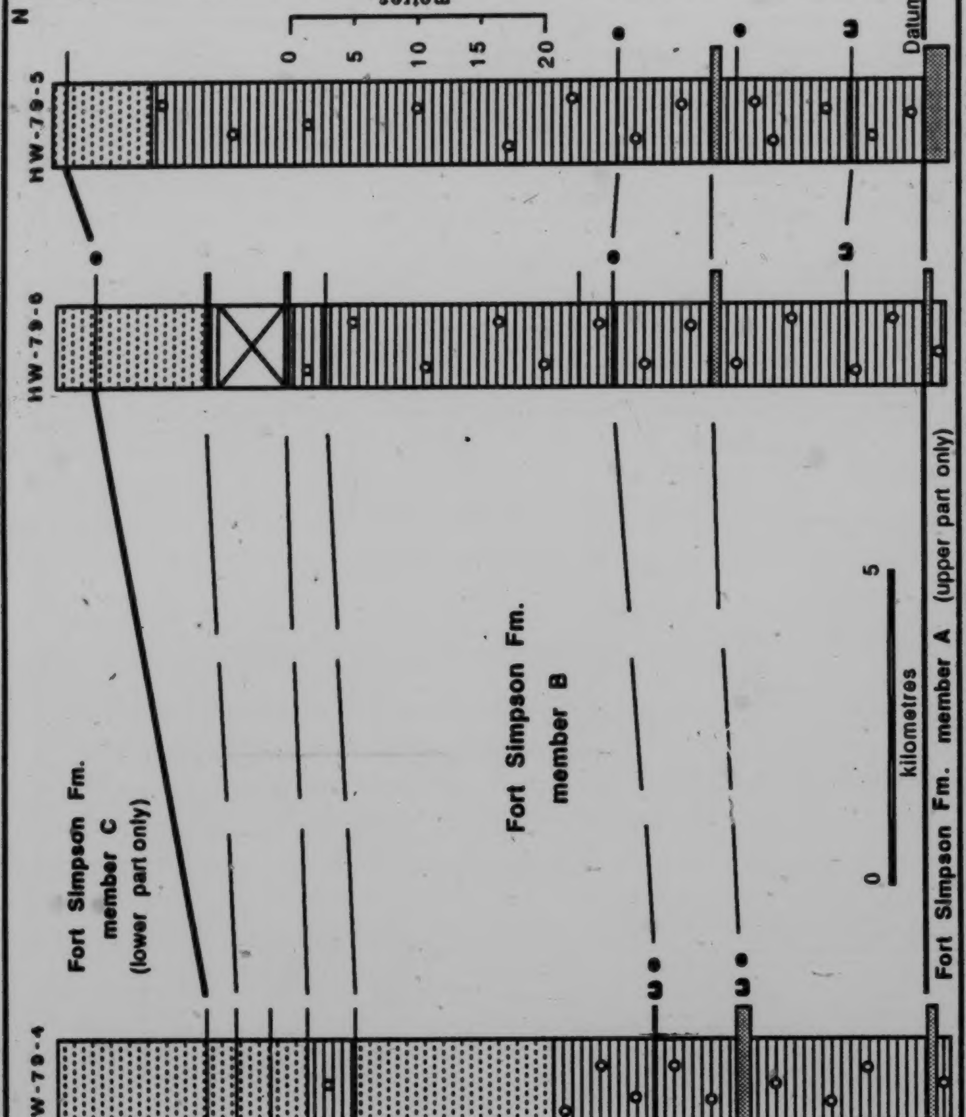


Figure 29. Part of cross section 1 showing correlations of member B of the Fort Simpson Formation. Vertical exaggeration is 200 times.

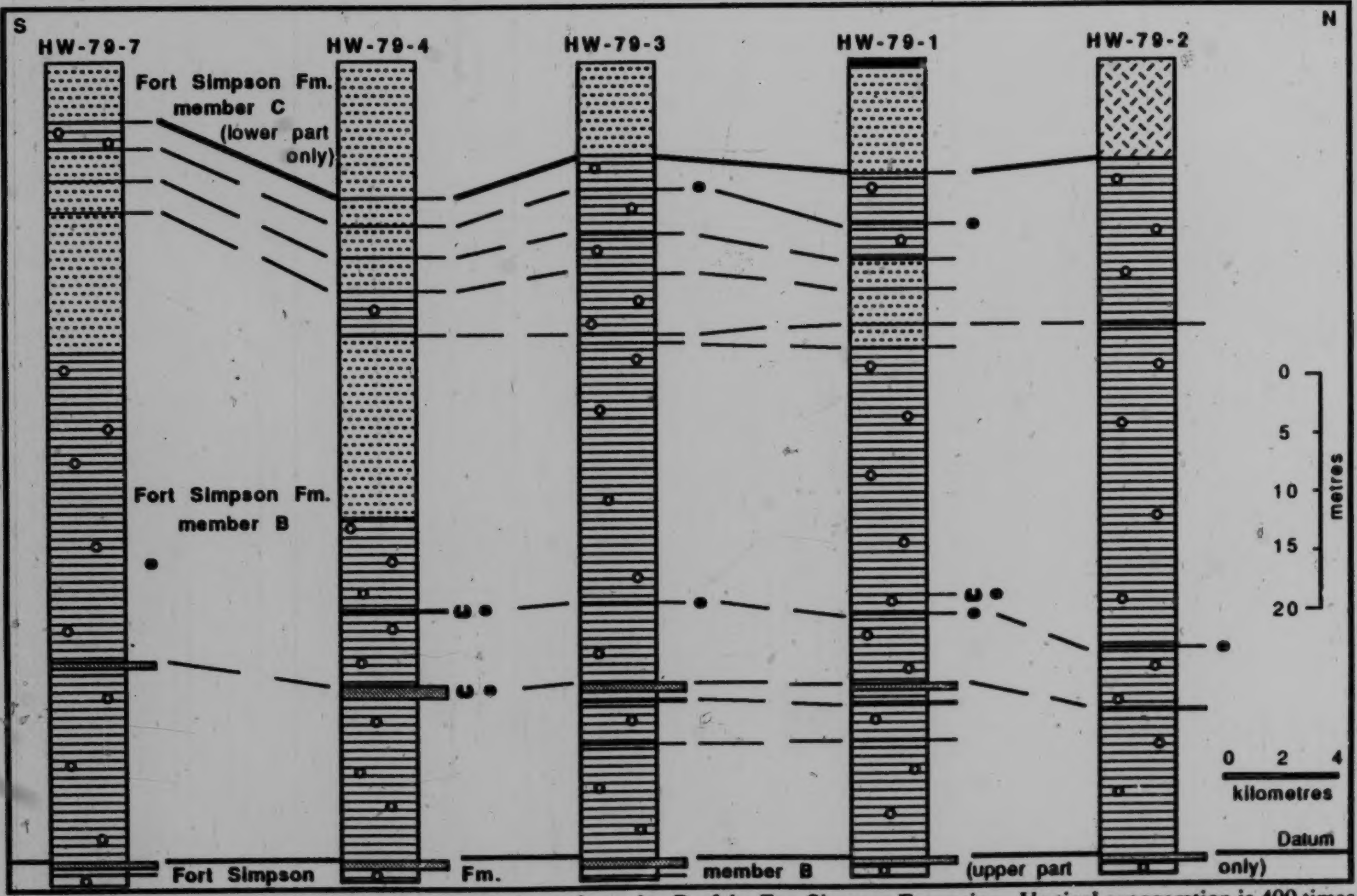

S
N
HW-79-7
HW-79-4
HW-79-3
HW-79-1
HW-79-2
Fort Simpson Fm. member C (lower part only)
Fort Simpson Fm. member B
0
5
10
15
20
metres
0 2 4
kilometres
Datum
Fort Simpson Fm. member B (upper part only)

Figure 30. Part of cross section 2 showing correlations of member B of the Fort Simpson Formation. Vertical exaggeration is 400 times.

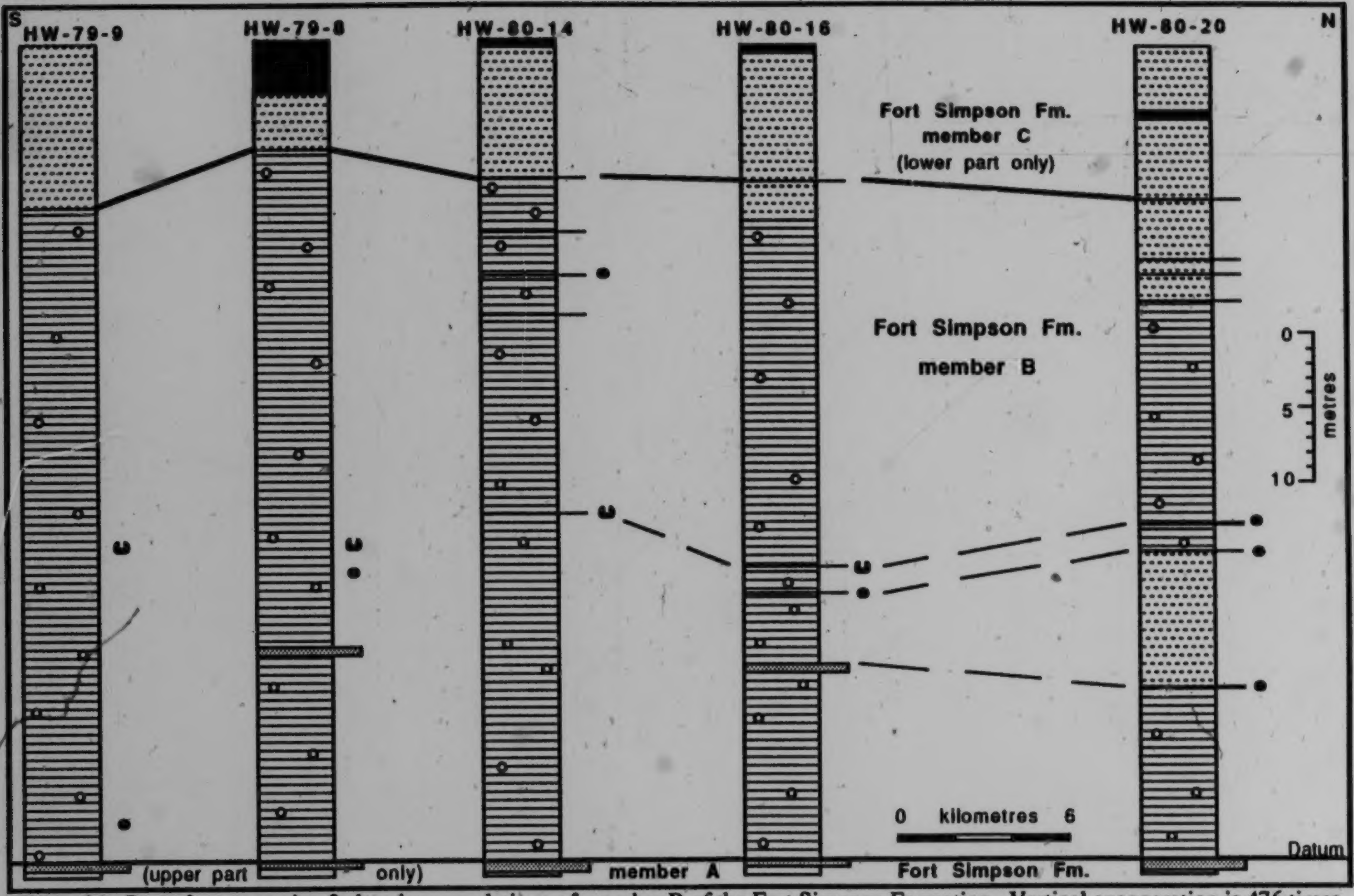


Figure 31. Part of cross section 3 showing correlations of member B of the Fort Simpson Formation. Vertical exaggeration is 476 times.

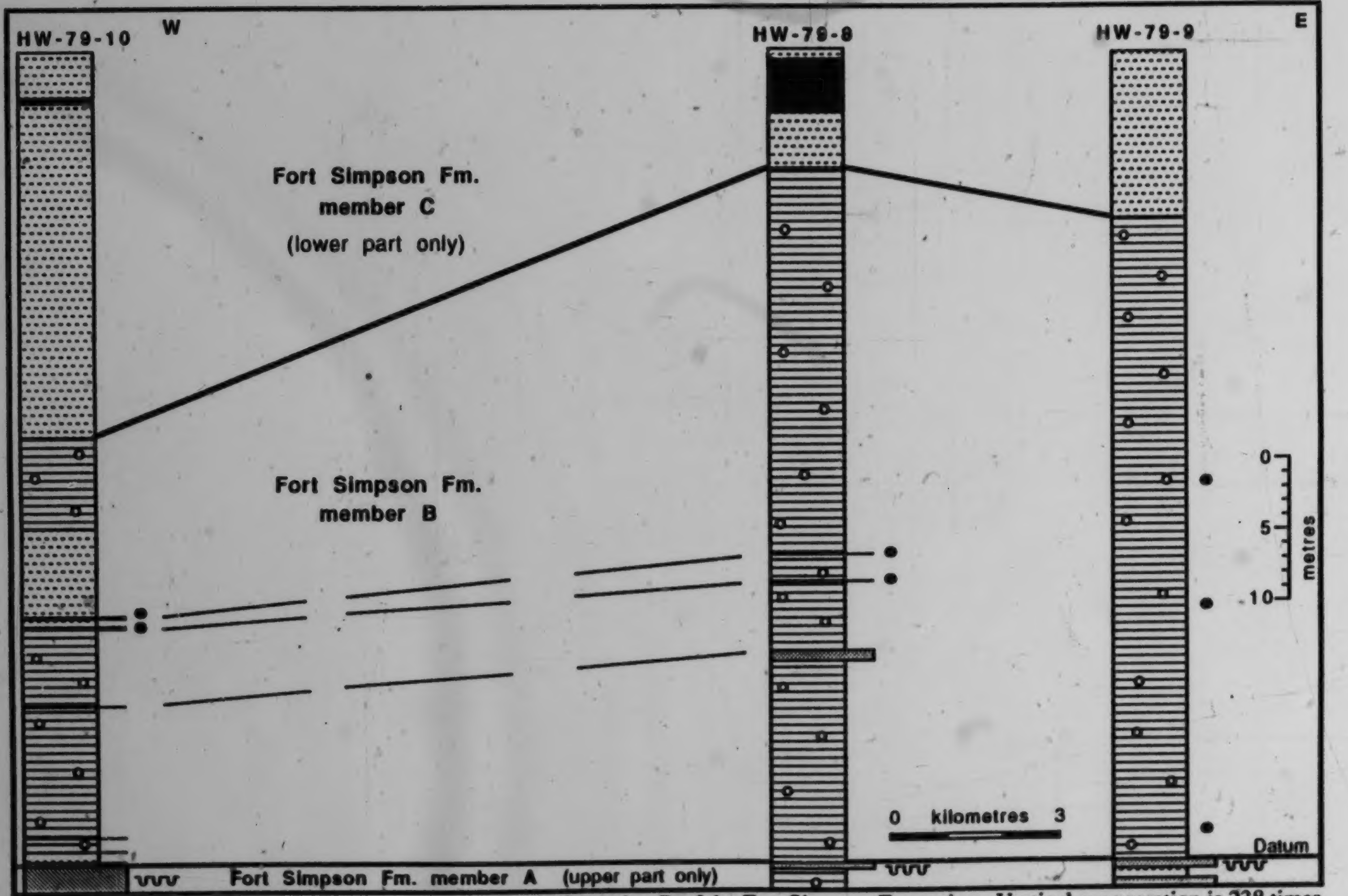


Figure 32. Part of cross section 4 showing correlations of member B of the Fort Simpson Formation. Vertical exaggeration is 238 times.

Lithology

The main lithology in member B is green grey, fissile, calcareous shale with argillaceous limestone nodules (Plate 3C). The limestone nodules are light green grey in colour, generally unfossiliferous, and range in size from 0.1 to 10 cm in diameter. Although they are commonly irregular in shape some are ovoid to spherical. In places the nodules resemble burrows, similar to those seen in the shales of member A (Plate 4A). The boundaries of the nodules are generally sharp. The shale locally contains thin intervals (1 to 20 cm thick) in which abundant disarticulated *Nervostrophia* sp. and crinoid ossicles float in a shale matrix. Brachiopods collected from member B include *Devonoproductus* sp., *Eleutherokomma* sp., *Atrypa* sp. and *Schizophoria* sp. (written comm., B. Jones, 1986).

Locally, member B contains a number of thin limestone beds (Figs. 29 to 32). These range from 0.3 to 1 m in thickness, the average being approximately 5 to10 cm. They are commonly intensely to completely bioturbated, dark to medium brown grey to green grey, fossiliferous wackestones to packstones. Many of these beds can be correlated between wells, while others appear to be laterally discontinuous (Figs. 29 to 32).

An interesting feature of the limestone beds is the occurrence in them of dark grey to black limestone pebbles. The pebbles commonly contain *Trypanites* sp. The bored black pebbles may represent the remnants of eroded and reworked submarine hardgrounds and/or early diagenetic concretions which were exhumed, bored and buried. They resemble the hiatus concretions described by Kennedy and Klinger (1972), Fürsich (1979) and Baird (1976, 1978, 1981).

Thickness and distribution

In the study area member B is 31 to 68 m thick (Figs. 29 to 32). The member thins gradually form east to west, with a few exceptions. Localized thins are present such as at HW-79-10 (Fig. 32). On cross-sections, member B closely parallels the underlying member A (Figs. 8 to 12).

H. Member C

Introduction

In the reference section HW-79-9 the 128.8 m (327.5 to 197.8 m) of green grey calcareous shale and very calcareous shale to very argillaceous mudstone are herein referred to member C of the Fort Simpson Formation (Fig. 23). It overlies calcareous shales with limestone nodules of member B and is overlain by calcareous shale with thin limestone beds of member D (Fig. 23).

Upper boundary

In the reference section the upper boundary of member C, which occurs at a depth of 197.8 m, is placed at the contact between green grey, calcareous shales of member C and green grey, calcareous shale with argillaceous limestone nodules, at the base of member D (Fig. 23). The nodule bearing unit at the base of member D occurs mainly in the southern part of the study area (Figs. 33 to 35). Toward the north this unit is absent and the upper boundary of member C is placed at the contact between calcareous shale and the base of a thin, calcareous siltstone to fine sandstone or quartzose mudstone bed at the base of member D (Figs. 33, 34).

The contact between members C and D occurs in section HR-99 (Fig. 33) where it is placed at the base of a 50 cm thick, bioturbated, grey green, calcareous siltstone to fine sandstone bed, located approximately 1 m above river level (Plate 2C). The shales, immediately below the siltstone at the base of member D, contain abundant 1 to 3 cm thick, siltstone stringers and lenses, giving them a rubbly appearance (Plate 4B).

The upper boundary of member C on geophysical logs is picked at the base of a thin limestone bed represented by a relatively low gamma "kick" and a corresponding high neutron count (Fig. 12). Member C is characterized by irregular gamma-ray and neutron log profiles. The profiles show a number of gentle bulges (Fig. 12) which occur over intervals of 10 to 30 m. These bulges, toward lower gamma and higher neutron counts, correspond to sections of member C in which the shales are more calcareous than normal. In these areas the shales grade into rocks with compositions between argillaceous limestones and very calcareous mudrock.

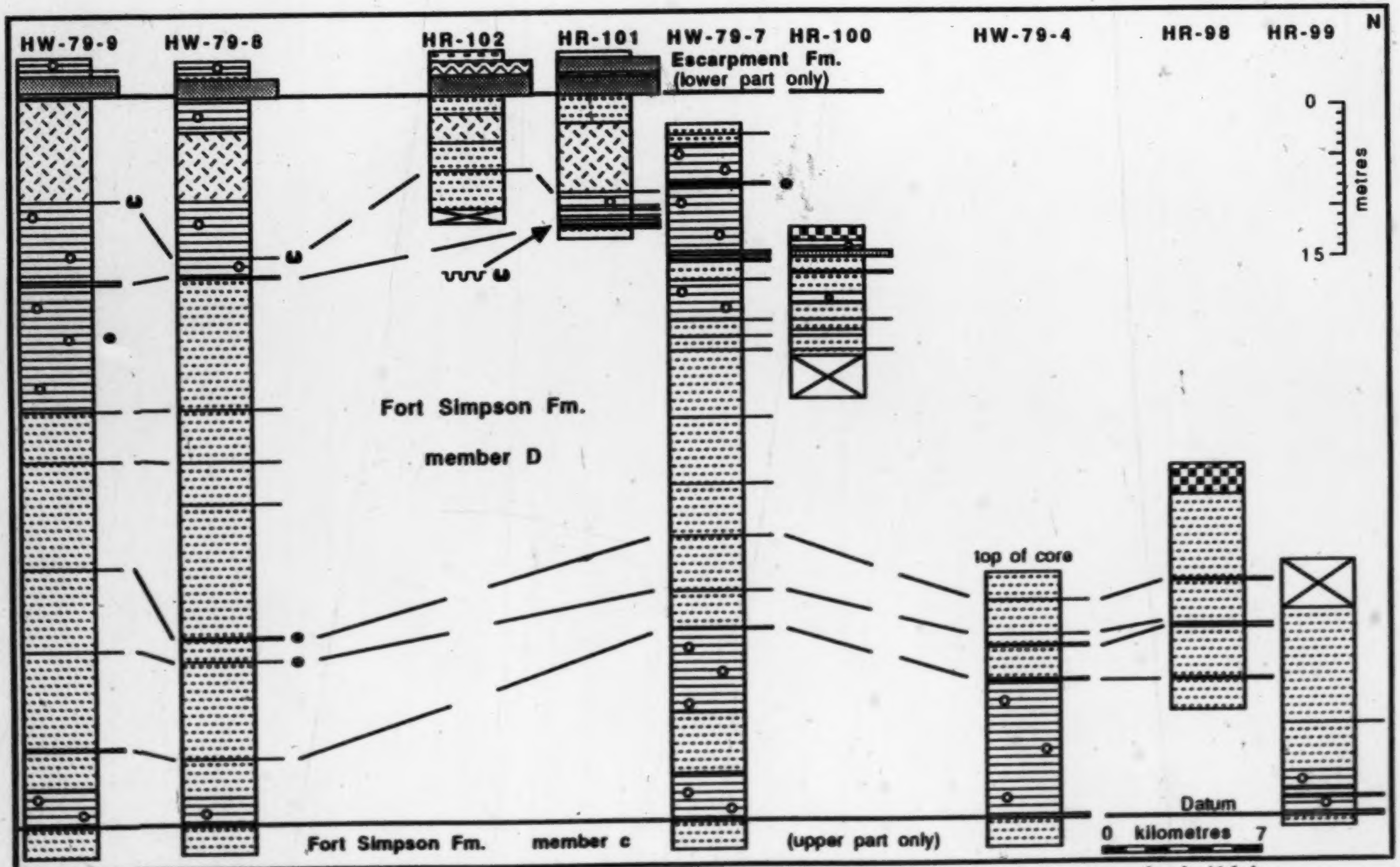


Figure 33. Part of cross section 1 showing correlation of member D of the Fort Simpson Formation. Vertical exaggeration is 416 times.

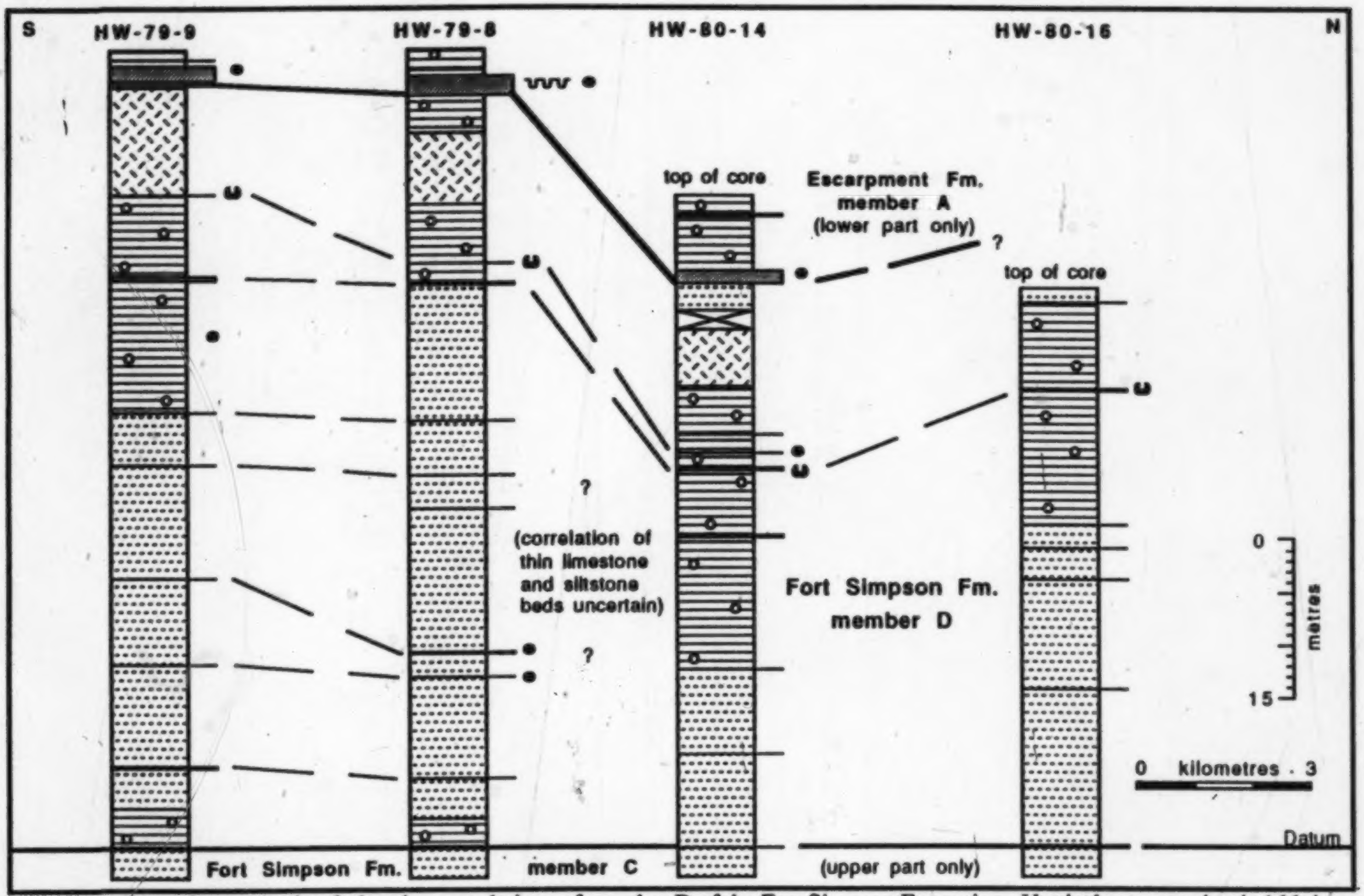


Figure 34. Part of cross section 3 showing correlations of member D of the Fort Simpson Formation. Vertical exaggeration is 166 times.

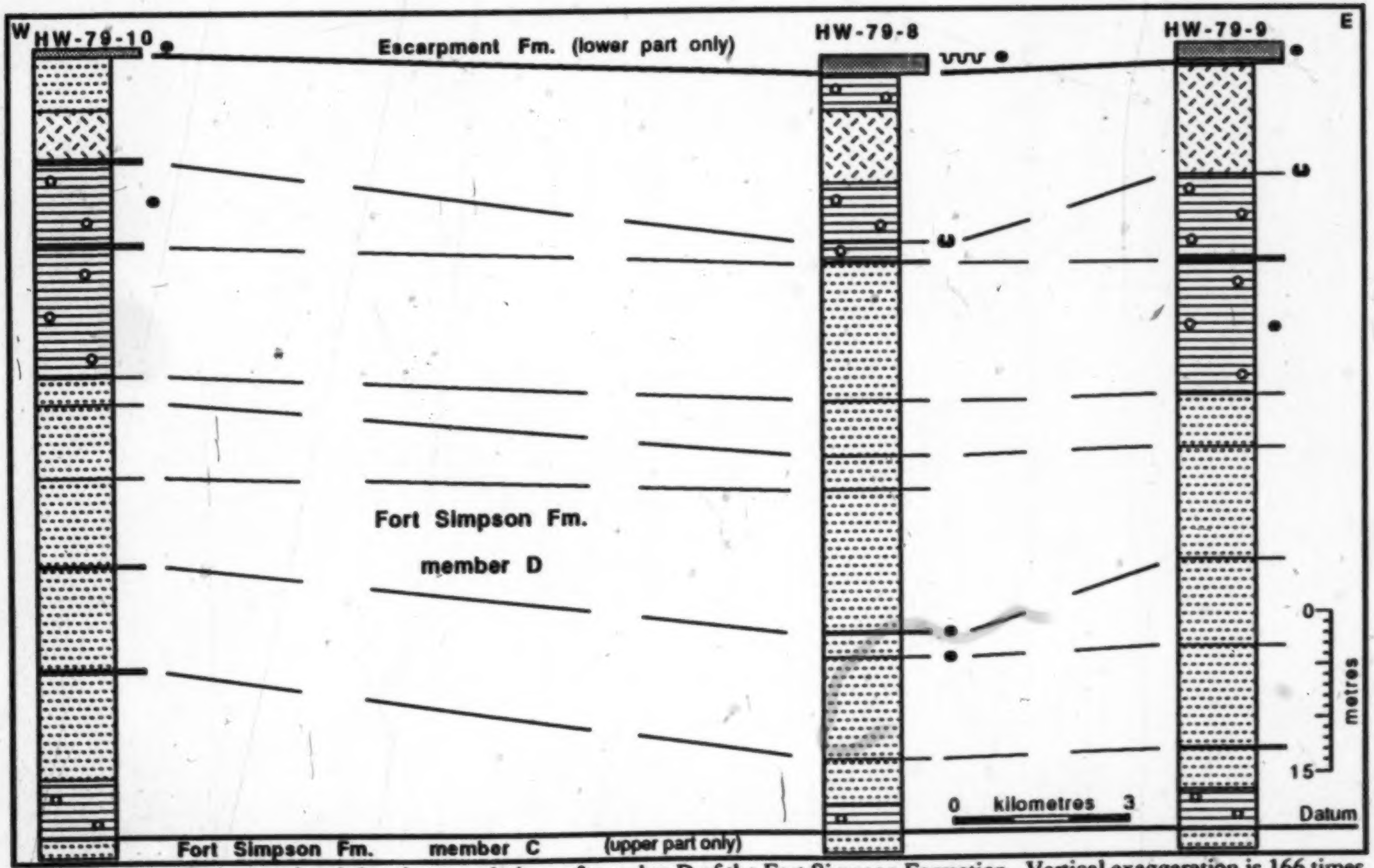


Figure 35. Part of cross section 4 showing correlations of member D of the Fort Simpson Formation. Vertical exaggeration is 166 times.

Nature of contact

In the reference section and some of the other sections, the contact between members C and D is gradational. This contact is represented by a change from calcareous shale to calcareous shale with limestone nodules and, therefore, its placement is somewhat arbitrary (Figs. 33 to 35). However, the contact appears to maintain a relatively constant stratigraphic position, and so the choice of this boundary appears justified. Where the boundary is placed at the base of the calcareous siltstone to quartzose limestone at the base of member D, the contact is sharp (Plate 4B).

Lithology

Member C consists mainly of green grey, calcareous, fissile shale. The shales and mudrocks commonly contain 0.1 to 0.3 cm thick, silty, argillaceous, green grey to orange grey, limestone stringers. These are commonly finely laminated, laterally discontinuous and always less than 3 cm long. Locally, member B contains light grey green, indurated to slightly fissile, (Plate 3D) calcareous mudrock, or very argillaceous limestone (mudstone). It was difficult to establish the boundaries of these units due to the gradational nature of their contacts. Therefore, they are all included as calcareous shale. A clue to the distribution of these units can be obtained from the geophysical logs where they are characterized by increased neutron and decreased gamma counts, in comparison to the typical shales of member C (Fig. 12).

Locally, a unit of dark brown to black, noncalcareous, very finely laminated shale (Plate 3E) occurs just above the base of member C (Figs. 30 to 32). This unit varies in thickness from 0.7 to 5 m. The shales are easily recognized by their dark colour and provide a useful marker throughout most of the area. The upper and lower boundaries of this unit are gradational with interlaminated light and medium green grey, calcareous to noncalcareous shale.

Thickness and distribution

Member C is 125.4 to 149.5 m thick. The distribution of the member appears to parallel that of the underlying strata (Figs. 8 to 11). In general, where the underlying strata are relatively thin member C is thicker and *vice versa*. Member C thins gradually from the northeast to the southwest (Fig. 12).

I. Member D

Introduction

In the reference section HW-79-9 the 77.7 m (197.8 to 120.1 m) of green grey calcareous shale and lesser amounts of calcareous shale with limestone nodules, containing thin beds of calcareous siltstone and argillaceous, variably quartzose limestones, is herein informally referred to member D (Fig. 23).

This unit is considered to be part of the Fort Simpson Formation because the primary lithology is calcareous shale. Many of the thin interbeds in the shale consist of very fine sandstone to siltstone with some quartzose limestone beds, which appear to be transitional to those in the Escarpment Formation. These lithologies closely resembles those of the Fort Simpson Formation to the west of the study area, as described by Belyea and McLaren (1962).

Upper boundary

In the reference section the upper boundary of member D, which occurs at a depth of 120.1 m, is placed at the contact between mottled green grey and maroon, silty, calcareous shale, and the base of an intensely bioturbated, calcareous, slightly dolomitic siltstone at the base of the Escarpment Formation (Plate 5C). Most of member D is exposed discontinuously between measured sections HR-99 to HR-102 (Fig. 33).

On geophysical logs the upper boundary of member D is placed at the base of a low gamma and high neutron count "kick" (Fig. 12). This corresponds to the calcareous siltstone or quartzose limestone at the base of the Escarpment Formation (Fig. 12).

Lithology

Member D consists primarily of green grey, calcareous, fissile shale and lesser amounts of calcareous shale with limestone nodules, silty shale and silty, mottled maroon and green grey shale. A characteristic feature of member D is the presence of a number of 1 to 50 cm thick (average 5 to 10 cm) interbeds of calcareous siltstone (Plate 4E) to very fine sandstone and variably quartzose limestone.

The limestone beds are variably fossiliferous and range from mudstone to grainstone in composition. They commonly contain abundant disarticulated brachiopods, ostracodes, and crinoid ossicles and rarely, bryozoan and coral fragments. Brachiopods collected from a limestone bed, 5.2 m above the base of section HR-102 include *Pseudoatrypa devoniana* (Webster), *Cyrtospirifer* sp. and strophomenid indet. (written comm., B. Jones, 1986). Brachipods collected from shales in HW-79-10, HW-79-9, and HW-79-8 include *Spinatrypa* sp. *Nervostrophia borealis* Pedder, *Eleutherokomma* sp. and *Montelasmina besti* Pedder (written comm., B. Jones, 1986). In many cases, brachiopod valves have a convex-up orientation forming shelter structures which are underlain by micrite or sparry calcite cements (Plate 4C). Most of the limestone beds are slightly to intensely bioturbated and have a mottled appearance; however, recognizable burrows are rare.

Orange brown to black, bored and unbored limestone pebbles occur locally in these beds (Figs. 33 to 35). Near the base of HR-101 (Plate 2D), in the upper part of member D, a well developed hardground occurs (Fig. 33). It is developed in a quartzose, slightly dolomitic limestone bed and contains large, bored, dark rimmed limestone pebbles that are 1 to 10 cm long.

Some limestone beds contain small, 0.1 to 0.6 cm, coated grains (Plate 4D). Intraclasts or abraded fossil fragments, most commonly brachiopod shells, are coated by irregular, discontinuous laminations of micrite and fine calcite spar. The number of laminations is quite variable and range in thickness from 0.01 to 0.05 mm thick. Fine disseminated pyrite crystals are closely associated with the laminations.

Beds consisting mainly of detrital quartz range from coarse siltstone to very fine sandstone. They are always calcareous and locally slightly dolomitic. They are commonly highly to completely bioturbated (Plate 4E); however, some vestige of the original fine, planar laminations is usually preserved. In outcrop these beds are slightly more recessive than the limestone beds and are commonly friable. In outcrop some of these beds contain well preserved trace fossils. At the base of section HR-99 (Fig. 33 - 1 m above base of section) *Rhizocorallium jenense* Zenker and *Planolites beverleyensis* Billings are preserved in the calcareous siltstone bed at the base of member D (Plate 4F). A 30 cm thick bed, located 3.1 m above the base of section HR-98 contained a high density of *Trichophycus* sp. and possible *Cruziana* sp.

Some beds in the upper part of member D show evidence of deposition by intense current activity. These commonly contain fine planar parallel, undulose parallel, to parallel cross-laminations, which are cross cut by vertical to subvertical, sharp walled burrows. In some cases, such as in the quartzose limestone bed located 18 m above the base of HR-100 (Fig. 33), the beds consist of a basal shell lag overlain by fine planar laminations grading up into low angle cross-laminations (Plate 5A). The basal lag has a sharp erosive base, commonly containing multidirectional sole marks, consists of abraded, disarticulated brachiopod valves and crinoid ossicles and is sharply overlain by the laminated unit. Shelter structures are formed by the convex-up orientation of some of the brachiopod valves. The laminated unit is cross cut by a low density assemblage of vertically to subvertically oriented trace fossils including *Planolites beverleyensis* Billings, *Diplocraterion parallelum* Torrell, *Cylindrichnus concentricus* Howard, *Skolithos linearis* Haldeman, and *Palaeophycus tubularis* Hall (pers. comm. S. G. Pemberton, 1987).

Some of the quartzose limestone beds near the top of member D contain well preserved trace fossil assemblages. A 30 cm thick quartzose limestone bed located 17.9 m above the base of section HR-100 contained an assemblage of *Planolites beverleyensis* Billings, *Skolithos linearis* Haldeman, *Monacraterion tentaculatum* Torrell, *Diplocraterion parallelum* Torrell, *Arenicolites*? *variablis* Fürsich, *Polycladichnus*? sp. and possible *Chondrites* sp. (pers comm. S. G. Pemberton, 1987). A bed of similar composition, located 1. 5 m above the base of HR-101, just above a well developed hardground, contained an assemblage consisting of *Skolithos linearis* Haldeman, *Trichophycus* sp., *Munsteria* sp., *Phycodes* sp. , *Chondrites* sp. and *Rhizocorallium* sp. (pers. comm. S. G. Pemberton, 1987).

In both cases the traces are undeformed and sharp walled, which might indicate that the sediment was firm at the time of burrowing.

Many of the limestone beds near the lower part of member D can be traced for several kilometres (Figs. 33 to 35). However, the beds become more difficult to correlate toward the upper part of the member. This is probably a result of the sporadic nature of the exposures along Hay River.

Thickness and distribution

Member D of the Fort Simpson Formation is 57.9 to 78.9 m thick. In general, the thickness of member D remains relatively constant throughout the study area with the exception of the anomalous thickness in HW-80-14 (Fig. 34). The member thickens slightly from north to south (Fig. 12) but maintains a consistent thickness from east to west (Fig. 35).

VII. ESCARPMENT FORMATION

A. Introduction

In the reference section HW-79-9 the 105.8 m (120.1 to 14.3 m) of calcareous shale containing thick interbeds of calcareous siltstone to sandstone and bioclastic to biostromal limestones, is herein referred to the Escarpment Formation (Fig. 36). It is underlain by the calcareous shale of the Fort Simpson Formation and overlain by variably quartzose, dolomitic limestones of the Twin Falls Formation. The lower and upper boundaries of the Escarpment Formation are the same as those defined for the Escarpment Member of the Hay River Formation by Belyea and McLaren (1962). The Escarpment Formation contains a number of thick resistant limestone and siliciclastic beds which are well exposed along Hay River (Plates 5 to13).

Belyea and McLaren (1962) placed the upper boundary of the Escarpment Member of the Hay River Formation at the contact between light olive grey, current bedded, calcareous sandstone and yellow grey quartzose limestone, with some argillaceous partings, at the base of the overlying Alexandra Member of the Twin Falls Formation. This contact is well exposed at the base of Alexandra Falls.

The Escarpment Member of the Hay River Formation as defined by Belyea and McLaren (1962) should be elevated to formational status following the suggestion of House and Pedder (1963). Jamieson's (1967) recommendation that the term Escarpment Formation of House and Pedder (1963) be discontinued because of miscorrelation is invalid because the upper and lower boundaries of the strata, here referred to the Escarpment Formation, are well exposed along Hay River and can be easily recognized in drill core and on geophysical logs. Therefore, if caution is excercised, there should be no mistake in the placement of the boundaries. Complete sections of the Escarpment Formation occur in HW-79-9 and HW-79-10 while partial sections occur in HW-79-8 and HW-80-14. Relatively complete exposures of the formation occur in outcrop between sections HR-101 and HR-108. The

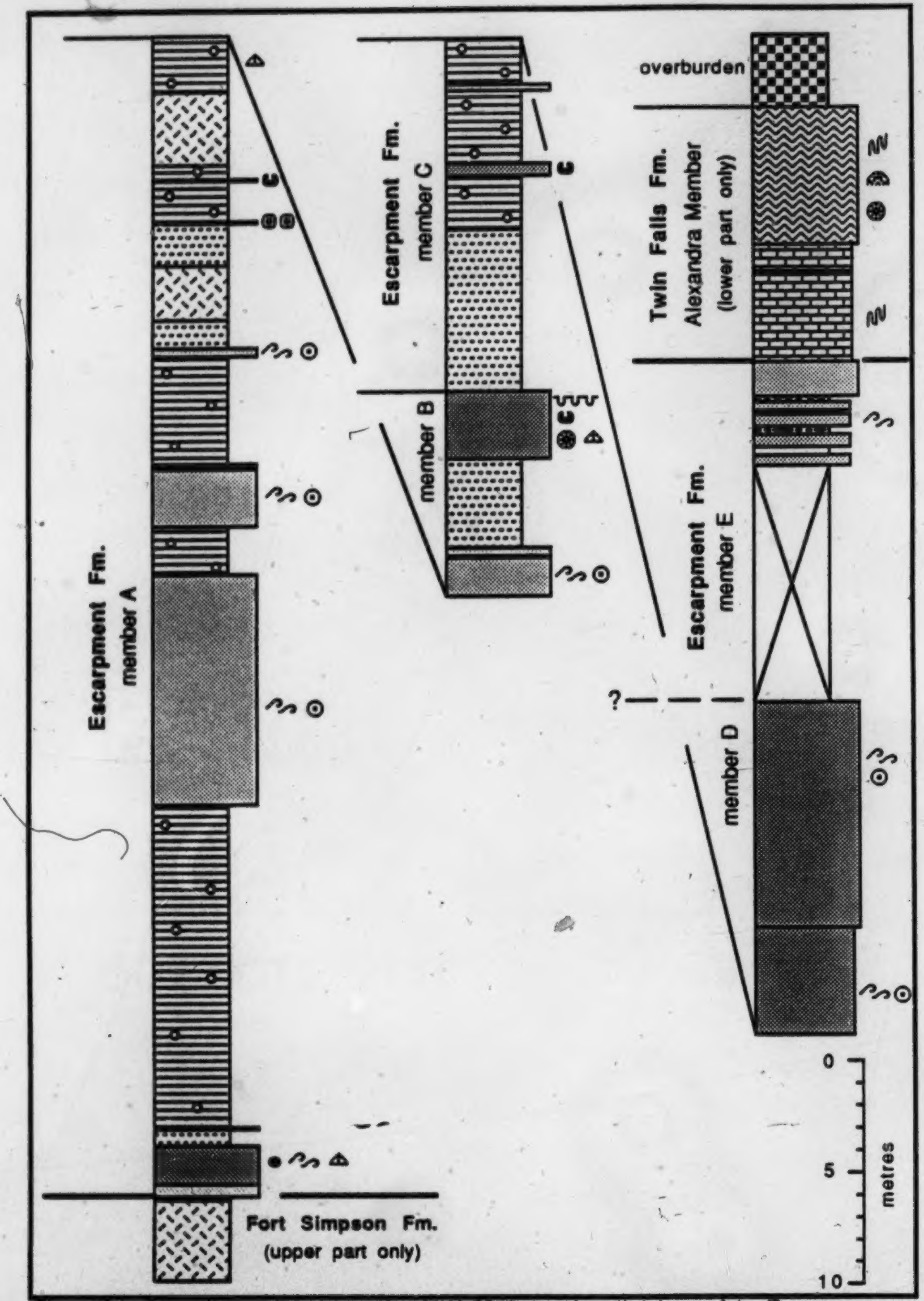


Figure 36. Part of the reference section HW-79-9 showing divisions of the Escarpment Formation and lower and upper contacts with the Fort Simpson and Twin Falls formations, respectively.

lower boundary of the formation is well exposed in sections HR-101, HR-102, HR-111 and HR-103, while the upper boundary is well exposed at the upper falls on Twin Falls Creek at section HR-108 (Plate 6B).

The Escarpment Formation is subdivided lithologically into the informal members A to E (Fig. 36). The boundaries of members A and B correspond to those defined by Jamieson (1968) for her members B and C of the Hay River Formation, respectively. The boundaries of members C, D, and E of the Escarpment Formation do not correspond to those defined by Jamieson (1968) for her members D, E, and F, respectively. However, the members are roughly equivalent, with the exception of the exact placement of the boundaries.

B. Upper boundary

In the reference section HW-79-9 the upper boundary of the Escarpment Formation is placed at the top of thinly planar laminated to cross-laminated, slightly bioturbated, light to medium grey, calcareous siltstone to very fine sandstone at the top of member E. This quartzose unit is overlain sharply by buff to light brown, stylolitized, thinly bedded, quartzose, dolomitic limestones, with thin carbonaceous seams, at the base of the Alexandra Member of the Twin Falls Formation (Fig. 36). In the reference section the contact occurs at a depth of 14.3 m. The lithologies above and below this contact remain relatively constant over a distance of about 20 km.

In core, the contact between the Escarpment Formation and the overlying Twin Falls Formation is recognizable by: (1) a colour change from light to medium grey rocks in the Escarpment Formation, to distinctive cream to buff coloured rocks in the Twin Falls Formation, (2) the distinct lithologic change from calcareous siltstone and sandstone of the Escarpment Formation to slightly quartzose, dolomitic limestone in the Twin Falls Formation, (3) the ubiquitous presence of stylolites in the carbonates of the Twin Falls Formation and the relative lack of these features in the Escarpment Formation, and (4) the lack of argillaceous material in carbonates of the Twin Falls Formation compared to the abundance of argillaceous material and shale interbeds in the Escarpment Formation.

In outcrop this boundary is more difficult to recognize due to the weathered nature of the rocks. The dolomitic limestones at the base of the Twin Falls Formation are slightly more recessive than the calcareous sandstones at the top of the Escarpment Formation. This is due to the fact that they have thin bedding and a flaggy weathering character (Plate 6B).

Locally, Jamieson's (1968) definition of the boundary between the Hay River and Twin Falls formations does not correspond to that defined by Belyea and McLaren (1962). At Twin Falls Creek, Jamieson (1968) noted that the boundary between member F of the Hay River Formation and the Alexandra Member of the Twin Falls Formation is placed at the first occurrence of colonial corals above the siltstones of member F. However, detailed correlations of section HR-108 (at Twin Falls Creek) and drill cores HW-79-9 and HW-79-10, show that the base of the Twin Falls Formation should be placed lower than that determined by Jamieson (1968). The boundary should be placed at the contact between light to medium grey, planar laminated to cross-laminated, slightly bioturbated, calcareous sandstone-siltstone at the top of the Escarpment Formation (Plate 5F) and buff to light brown, moderately bioturbated, thinly bedded, variably quartzose, stylolitic, dolomitic limestones, with thin, carbonaceous "horse tail" seams (Plate 6A) at the base of the Alexandra Member of the Twin Falls Formation. Therefore, at Twin Falls Creek, the contact between the Escarpment Formation and the Alexandra Member should be placed 4.9 m lower in the section. This would correspond to the top of Jamieson's (1968) unit 8 of her member F of the Hay River Formation, which she measured at the upper falls on Twin Falls Creek. The placement of this boundary more closely corresponds to that defined by Belyea and McLaren (1962) at the base of Alexandra Falls.

It is difficult to characterize the Escarpment Formation on geophysical logs, since only two of the holes that were logged penetrated the entire thickness of the formation (Fig. 12). In these holes the upper boundary of the Escarpment Formation is placed at the inflection in the gamma response, from high API values in the argillaceous strata of the Escarpment Formation to low values in the clean limestones at the base of the Twin Falls Formation (Fig. 12). In general, the log profile for the Escarpment Formation has intermediate gamma and neutron counts and an irregular "spikey" profile corresponding to the interbedded shale and limestone to sandstone lithologies (Fig. 12).

C. Nature of contact

In both drill core and outcrop the contact between green grey, calcareous siltstone to sandstone at the top of the Escarpment Formation and buff limestones at the base of the Twin Falls formation, is sharp but conformable.

D. Lithology

The Escarpment Formation consists of calcareous, variably coloured shale and thin to thick interbeds of variably argillaceous and fossiliferous limestone, quartzose limestone and calcareous siltsone to sandstone. Shales are variably silty and range in colour from green grey to mottled maroon and grey. Locally the shales contain abundant argillaceous to silty limestone nodules and fossils including brachiopods, crinoid ossicles and horn corals.

The limestone beds in the shales are variably fossiliferous, with abundant brachiopods, crinoid ossicles, and ostracodes. They are commonly bioturbated, argillaceous and quartzose and range in composition from mudstones to rudstones. Some beds are biostromal, consisting mainly of coral-stromatoporoid bindstones. These consist mainly of low domal to platy corals and encrusting stromatoporoids, with lesser amounts of horn corals, brachiopods, gastropods, goniatites and crinoid ossicles. Limestone beds become more massive toward the top of the formation and form steep cliff sections.

Interbeds of calcareous siltstone to sandstone occur throughout the formation. These consist mainly of variable amounts of detrital quartz and commonly contain ripple marks and planar and cross-laminations.

E. Thickness and distribution

The Escarpment Formation is 105.8 to 113 m thick. The formation thins from north to south (Fig. 12) but remains relatively constant in thickness from east to west.

F. Member A

Introduction

In the reference section HW-79-9 the 51.3 m (120.1 to 68.6 m) of calcareous shale, with thick interbeds of calcareous siltstone to sandstone and fossiliferous limestones, overlying calcareous shale of the Fort Simpson Formation and overlain by calcareous shale with interbeds of sandstone and shale, is herein referred to member A of the Escarpment Formation (Fig. 36). This member corresponds to member B of the Hay River Formation as defined by Jamieson (1968).

Upper boundary

In the reference section the upper boundary of member A, which occurs at a depth of 68.6 m, is placed at the contact between calcareous shale with argillaceous to silty limestone nodules and the base of a 2.2 m thick, green grey, laminated to highly bioturbated, calcareous siltstone at the base of member B of the Escarpment Formation (Fig. 36).

The upper boundary of member A is recognizable throughout the area in both drill core and outcrop sections. Toward the west the boundary is slightly more difficult to place, however, because the siltstone at the base of member B thins from 2.2 to 0.9 m (Fig. 37). The lithology of this bed remains relatively consistent, however, and the boundary can be placed accurately. In outcrop the upper boundary of member A is well exposed in sections HR-104, HR-110, HR-105, HR-107, and HR-106 (Figs. 38, 39). It is easily recognizable because of the resistant nature of the calcareous siltstone to quartzose limestone bed at the base of member B (Plate 6C).

On geophysical logs the upper boundary of member A is placed at the base of a distinctive low gamma and high neutron "kick". This corresponds to the siltstone bed at the base of member B.

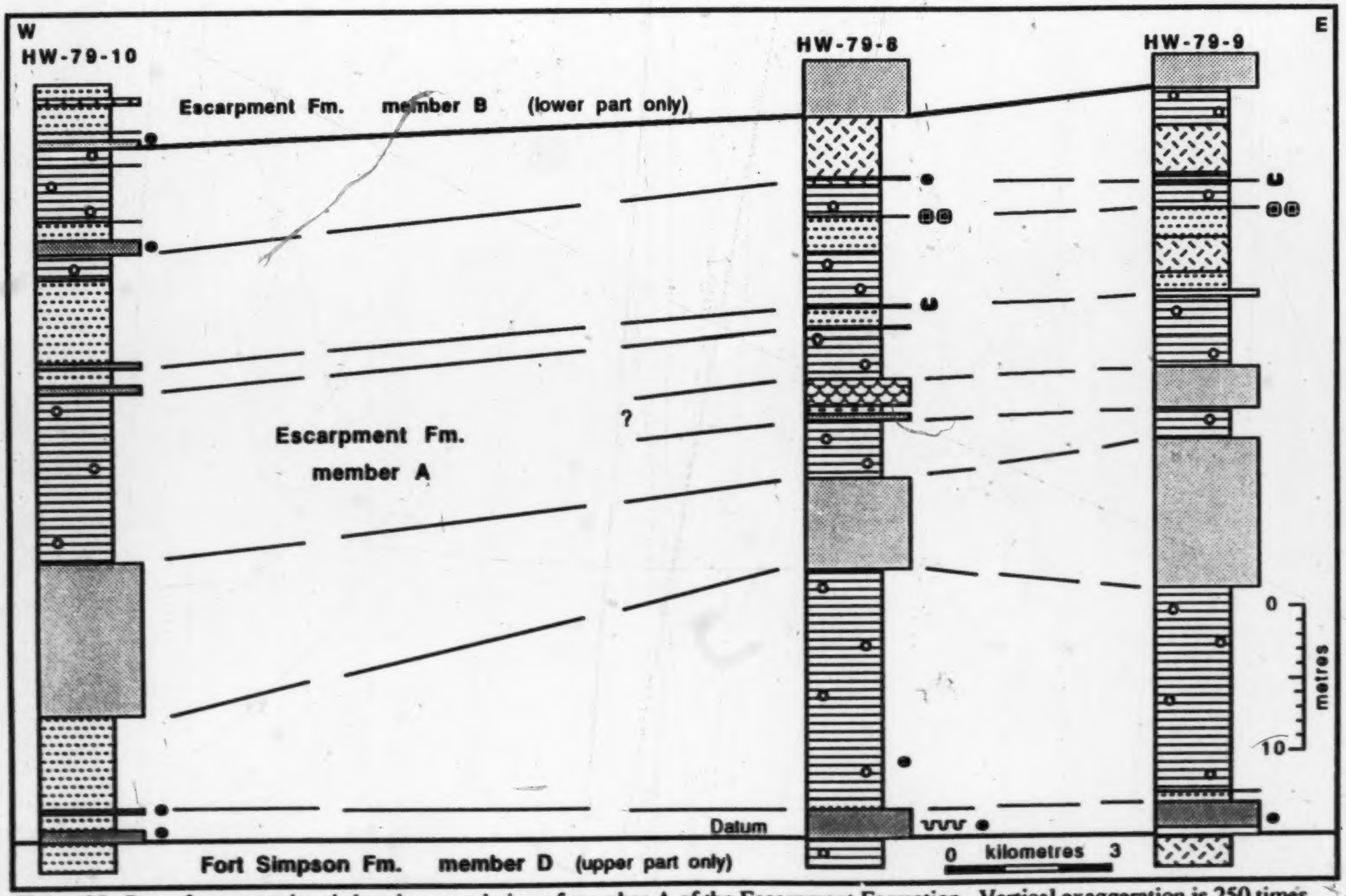

W
HW-79-10
HW-79-8
HW-79-9
E
Escarpment Fm. member B (lower part only)
Escarpment Fm.
member A
?
0
10
metres
Datum
Fort Simpson Fm. member D (upper part only)
0 kilometres 3

Figure 37. Part of cross section 4 showing correlation of member A of the Escarpment Formation. Vertical exaggeration is 250 times.

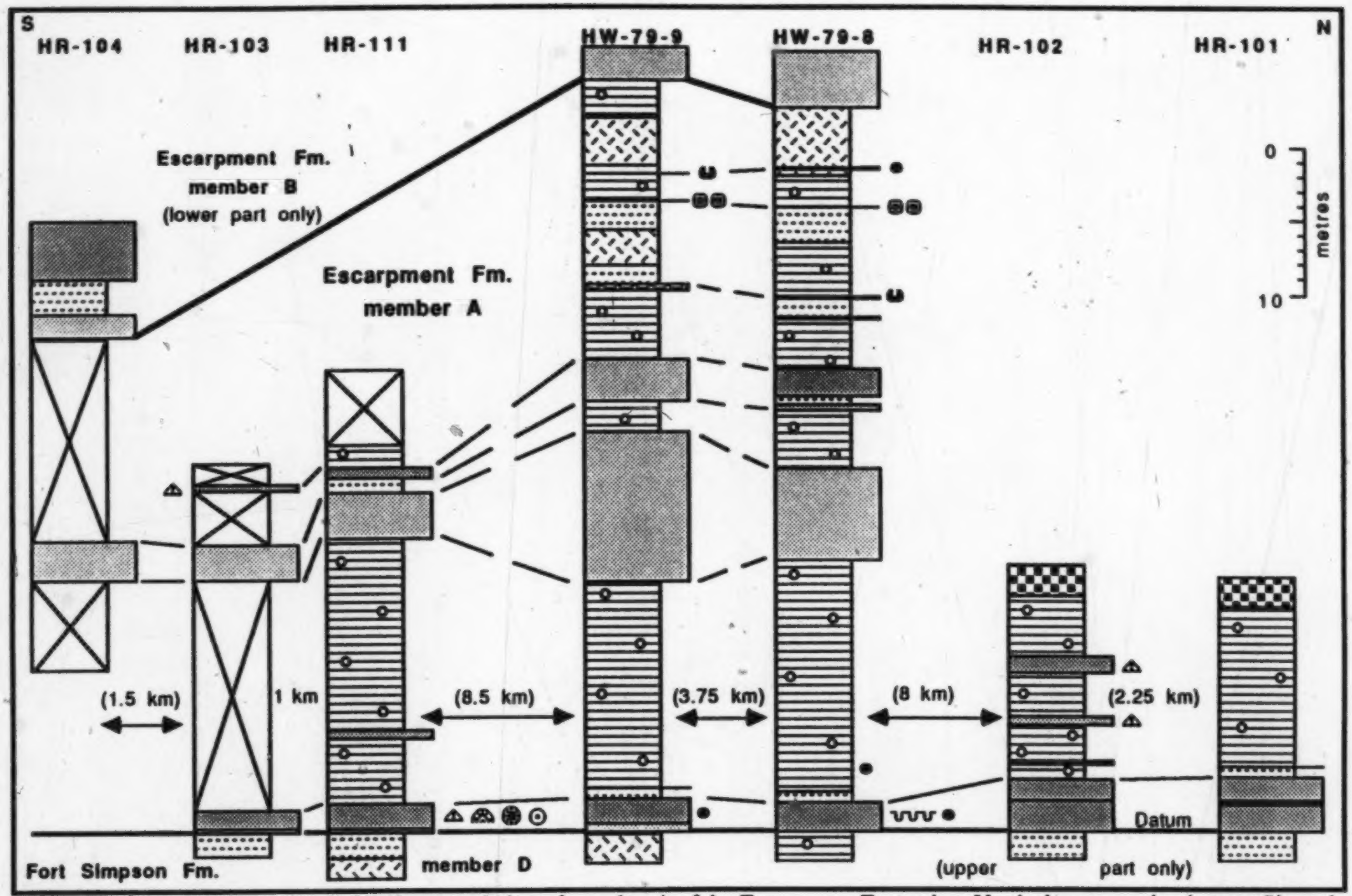


Figure 38. Part of cross section 1 showing correlation of member A of the Escarpment Formation. Vertical exaggeration is approximately 250 times.

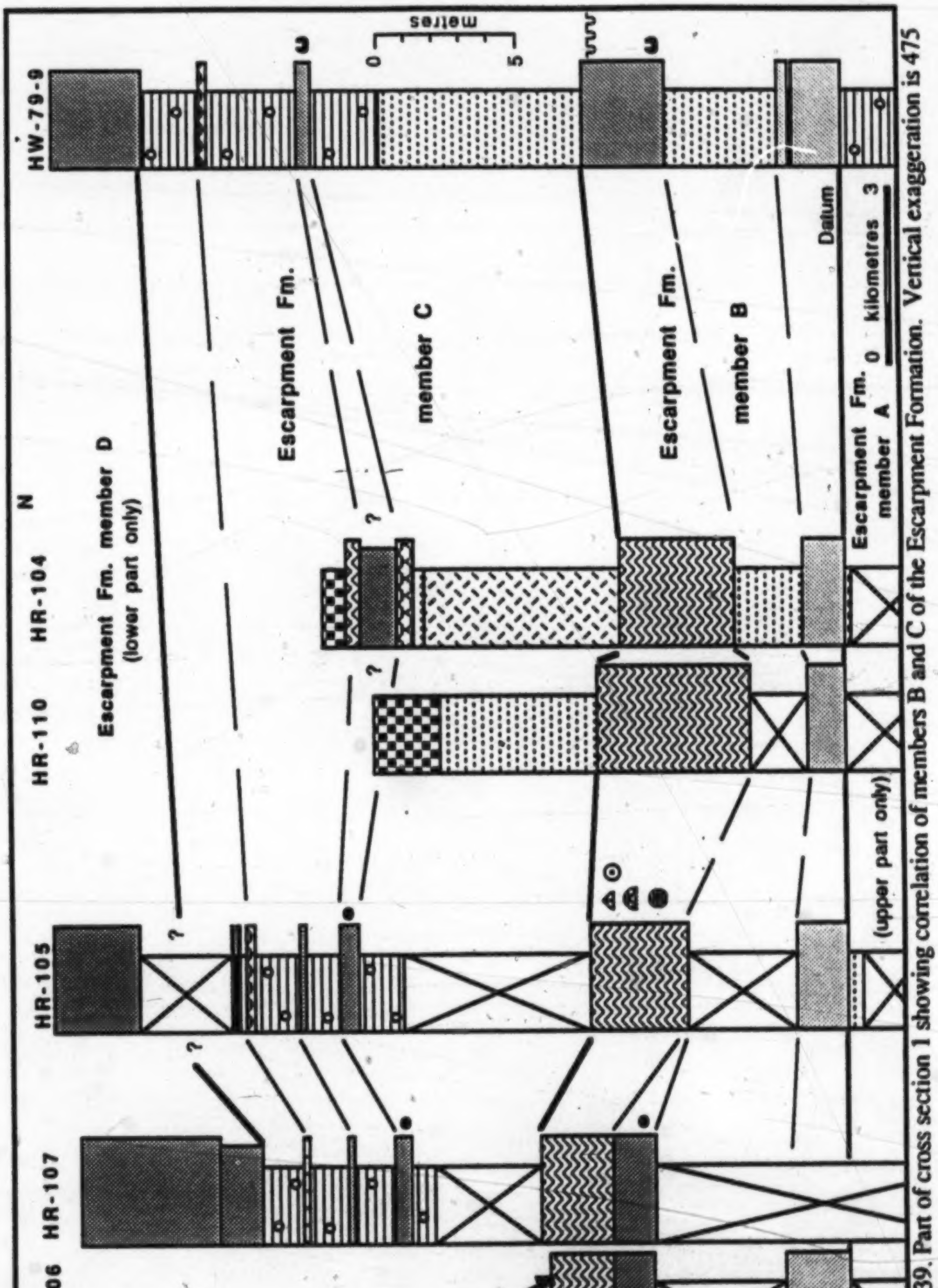


Figure 39. Part of cross section 1 showing correlation of members B and C of the Escarpment Formation. Vertical exaggeration is 475 times.

Nature of contact

The contact between members A and B of the Escarpment Formation is sharp throughout the study area. The nature of the contact is best observed in outcrop where the resistant, calcareous siltstone to quartzose limestone at the base of member B forms a sharp overhang above calcareous, silty shales of member A (Plate 6D).

Lithology

Member A consists primarily of calcareous, fissile to blocky, green grey shale, with some silty, calcareous shale. Near the top of the member silty, calcareous, mottled maroon and grey shales are common. Locally, below the contact with member B, these shales grade laterally into calcareous green grey, silty shale with limestone nodules (Figs. 37, 38). Limestone nodules in the shales of member A are argillaceous and silty and commonly have sharp boundaries. The nodules are commonly arranged in a bedded fashion, with individual flattened to oval nodules alligned but not touching (Plate 6E). Locally, where these nodules are concentrated in 20 to 50 cm thick beds, they form relatively prominent ledges in the more recessive calcareous shales (Plate 6E). Brachiopods collected from this shale unit at 26.95 m above the base of section HR-101 include *Cyrtospirifer* sp., *Spinatrypa* sp., and *Nervostrophia vestita* Crickmay (written comm., B. Jones, 1986).

The shales commonly contain silty limestone stringers, 0.1 to 0.3 cm wide and 1 to 2 cm long. Locally they are slightly to moderately bioturbated resulting in the mottled appearance of the maroon and grey shales near the top of the member.

Member A contains three widely mappable, prominent, limestone to siltstone beds (Figs. 37, 38). A 0.9 to 3.6 m thick unit comprising calcareous, quartz siltstone, overlain by argillaceous, variably quartzose, highly fossiliferous limestone occurs at the base of member A. The average thickness of the bed is 2.3 m and it thins gradually toward the south and west (Figs. 37, 38). The basal siltstone is commonly planar laminated and locally contains a 1 to 2 cm thick shell lag at its base. The upper surface of the bed commonly contains asymmetrical ripples (Plate 5B) and traces of *Palaeophycus striatus* Hall, *Trichophycus* sp. (Plate 7A), *Diplocraterion* sp. (Plate 7B), *Chondrites* sp. or *Planolites montanus* Richter (Plate 7C) and *Palaeophycus striatus* Hall, *Planolites montanus* Richter, *Trichophycus* sp. and possible *Thalassinoides* sp. (Plate 7D).

The overlying limestones (Plate 7E) are commonly moderately to highly bioturbated and range from wackestone to brachiopod-coral floatstones (Plate 7F). Corals are represented by colonial and solitary forms including, *Tabulophyllum* sp., *Alveolites* sp. and *Phillipsastrea* sp. Stromatoporoids occur more rarely, in some places encrusting corals. The limestones contain a rich brachiopod fauna that includes *Atrypa* sp., *Atrypa* sp. A, *Atryparia* sp., *Calvinaria* sp., *Cyrtospirifer thalattodoxa* Crickmay, *Nervostrophia vestita* Crickmay, *Productella*? sp., *Pseudoatrypa devoniana* (Webster), *Schizophoria mcfarlanei* Meek, *Spinatrypa* cf. *S. albertensis* Warren, *Spinatrypa* (*Invertrypa*?) sp., *Warrenella eclectea* Crickmay, *Eleutherokomma* sp., *Hypothyridina* cf. *H. emmonsi* Hall and Whitfield, and strophemenid indet. (written comm., B. Jones, 1986). Gastropods and goniatites (*Manticoceras*?) occur throughout the unit. The limestones commonly contain black limestone pebbles, and in one locality (HW-79-8) a hardground occurs near the top of the bed (Fig. 37).

The limestones at the base of member A are distinctive because of their rubbly weathered appearance in the field (Plate 7E). Harder limestone lumps (Plate 5E) are surrounded by more argillaceous limestone or rarely calcareous shale. The irregular shaped lumps are generally less fossiliferous than the surrounding matrix and appear to represent the fill of indistinct burrows. The surrounding argillaceous matrix weathers more rapidly giving the rubbly weathered appearance (Plate 5E). These limestones resemble the Type I and II limestones described by Jones *et al.* (1979) from the Late Silurian Read Bay Formation. Locally, branching burrows, with swelled turn-around junctions, resembling the ichnogenus *Thalassinoides*, are preserved in these beds (Plate 7F).

The rubbly limestone unit is overlain by 6.3 to 18 m (average of 14.2 m) of recessive, calcareous shale with limestone nodules containing a number of 0.1 to 1.2 m thick interbeds of light to medium green grey, argillaceous limestone. These consist primarily of moderately bioturbated, fossiliferous wackestones to packstone, containing abundant abraded brachiopods, crinoid ossicles and some gastropods. However, massive, unfossiliferous mudstones also occur. Brachiopods collected from the two stratigraphically highest beds in section HR-102 (Fig. 38) include *Calvinaria* sp., *Spinatrypa* cf. *S. albertensis* Warren, *Pseudoatrypa* cf. *P. devoniana* (Webster), *Cyrtospirifer thalattodoxa* Crickmay, *Cyrtospirifer*?sp., *Atrypa* sp., and strophomenid indet. (written comm., B. Jones, 1986).

Toward the middle part of member A, a thin to medium bedded unit, consisting mainly of highly to intensely bioturbated, green grey, calcareous, argillaceous siltstone (Plate 8A), occurs (Figs. 37, 38). It is 2.4 to 10.3 m thick (average of 5.8 m) and thins toward the south and west. The thickest sections occur in drill core. This large variation in thickness values may be a preservational feature. The complete unit is present in drill core whereas parts of the unit may have been covered or may be slightly recessive in outcrop. This middle resistant unit is bounded above and below by calcareous, silty shale with limestone nodules and some thin siltstone and fossiliferous limestone beds. It is variable in composition and grades laterally from calcareous siltstone or very fine sandstone to quartzose limestone. Fossils are locally abundant and include brachiopods (*Nervostrophia* sp., *Cyrtospirifer thalattodoxa* Crickmay, *Desquamatia* sp.), crinoid ossicles, and rarely corals (*Alveolites* sp.). However, some beds contain only rare, thin stringers and lenses of crinoid ossicles.

The middle limestone unit has a massive, prominent weathering character (Plate 8B, 8C) in the field. It is well exposed near the top of section HR-111 (Plate 8B, 8C) and HR-103 and the lower part of section HR-104 (Fig. 38). It is more resistant than the bed exposed at the base of member A and forms a prominent ledge (Plate 8B). It has a subtle rubbly appearance, due in part to the argillaceous content of some of the thin beds (Plate 8C) and enhanced locally, by the presence of a high density of possible traces of *Rhizocorallium* or *Cruziana*. These are well exposed on some of the bedding planes (Plate 8D).

This middle limestone unit is overlain by a recessive shale unit which is 1.0 to 3.9 m thick, with an average thickness of 3.2 m (Fig. 37) and consists mainly of green grey calcareous, silty shale, with some calcareous, argillaceous, silty limestone nodules. Locally, brachiopods and other fossil debris are scattered throughout the shale unit. Brachiopods collected 25.1 m above the base of section HR-103, include *Cyrtospirifer glaucus*?Crickmay, *Pseudoatrypa devoniana* (Webster), *Schizophoria mcfarlanei* Meek, *Nervostrophia borealis* (Pedder) and strophomenid indet. (witten comm., B. Jones, 1986).

The recessive unit is overlain by a resistant siltstone unit, which occurs near the middle of member A (Figs. 37, 38), comprising moderately to highly bioturbated, finely laminated, medium green grey, slightly dolomitic, calcareous siltstone. Fine laminations are disrupted by vague horizontal burrows. The unit is 0.4 to 2.8 m thick (average of 1.5 m). In general, it thins toward the south (Fig. 37) and to the west, grades into silty shale (Fig. 38).

Above the resistant siltstone bed, member A consists of a variety of shales (Figs. 37, 38) with thin interbeds of bioclastic limestone and calcareous siltstone that are 10 to 50 cm thick (average of 10 to 15 cm). The limestone beds range from mudstone to fossiliferous grainstone. Some of the packstones to grainstones contain shelter structures beneath convex-up brachiopod valves (Plate 8E). Fossil debris is generally abraded and consists mainly of disarticulated brachiopods, crinoid ossicles and ostracodes. These beds commonly contain black to dark grey, or dark rimmed, bored and unbored limestone pebbles. In some cases these are the main allochem and the limestones can be characterized as black pebble packstones to floatstones (Plate 8F).

Many of these beds show features indicative of deposition by high energy currents, possibly of storm origin. These include the presence of crude grading of bioclasts, parallel orientation of convex-up shells commonly preserving shelter structures, planar to cross-laminations, and black pebbles and intraclasts.

An interesting feature of this part of member A is a thin (10 cm) ooid packstone which can be traced from HW-79-8 toward the south, over a distance of 3.75 kilometres, to HW-79-9 (Figs. 37, 38). This bed consist of 50 to 60% ooids, which have an average diameter of 0.4 mm (Plate 8G). The ooids are cemented by fine calcite spar. They are undeformed, stained by hematite, have a radial concentric texture and contain shell fragments as their nucleii. Many of the ooids have a radial inner cortex and an outer cortex composed of thin concentric bands of radially oriented crystals, while others have only a radial inner cortex (Plate 8G). These closely resemble the ooids described by Heller *et al.* (1980) and Medwedeff and Wilkinson (1983). The bed is very slightly bioturbated, containing *Planolites* sp. which are filled by idiotopic, euhedral dolomite crystals.

Thickness and distribution

Member A of the Escarpment Formation is 30.7 to 49.7 m thick. Based on the limited control it appears to thin toward the south and west (Figs. 12, 37, 38).

G. Member B

Introduction

In the reference section HW-79-9 the 9.1 m (68.6 to 59.5 m) of calcareous siltstone to sandstone, calcareous, green grey shale and bioturbated, fossiliferous mudstone, overlying interbedded shale, limestone and siltstone of member A and overlain by shale with thin limestone beds, is herein referred to member B of the Escarpment Formation (Fig. 36). This member corresponds to member C of the Hay River Formation as defined by Jamieson (1968).

Upper boundary

In the reference section the upper boundary of member B, which occurs at a depth of 59.5 m, is placed at the contact between a 2.9 m thick, medium brown grey, moderately to intensely bioturbated wackestone and green grey, calcareous, fissile shale (Plate 9A) at the base of member C (Fig. 36). The contact is well developed in both drill core and outcrop. The lithology at the upper boundary changes throughout the study area. The uppermost beds at the top of member B range from coral-stromatoporoid bindstones, argillaceous mudstones to grainstones and quartzose limestone (Figs. 39, 40).

In outcrop the upper boundary of member B is well exposed near the top of sections HR-104 (Plate 6C), HR-110 (Plate 9B), and HR-106 (Plate 9C) and near the middle of sections HR-105 (Plate 9D) and HR-107 (Plate 9E). The thick limestone unit at the top of

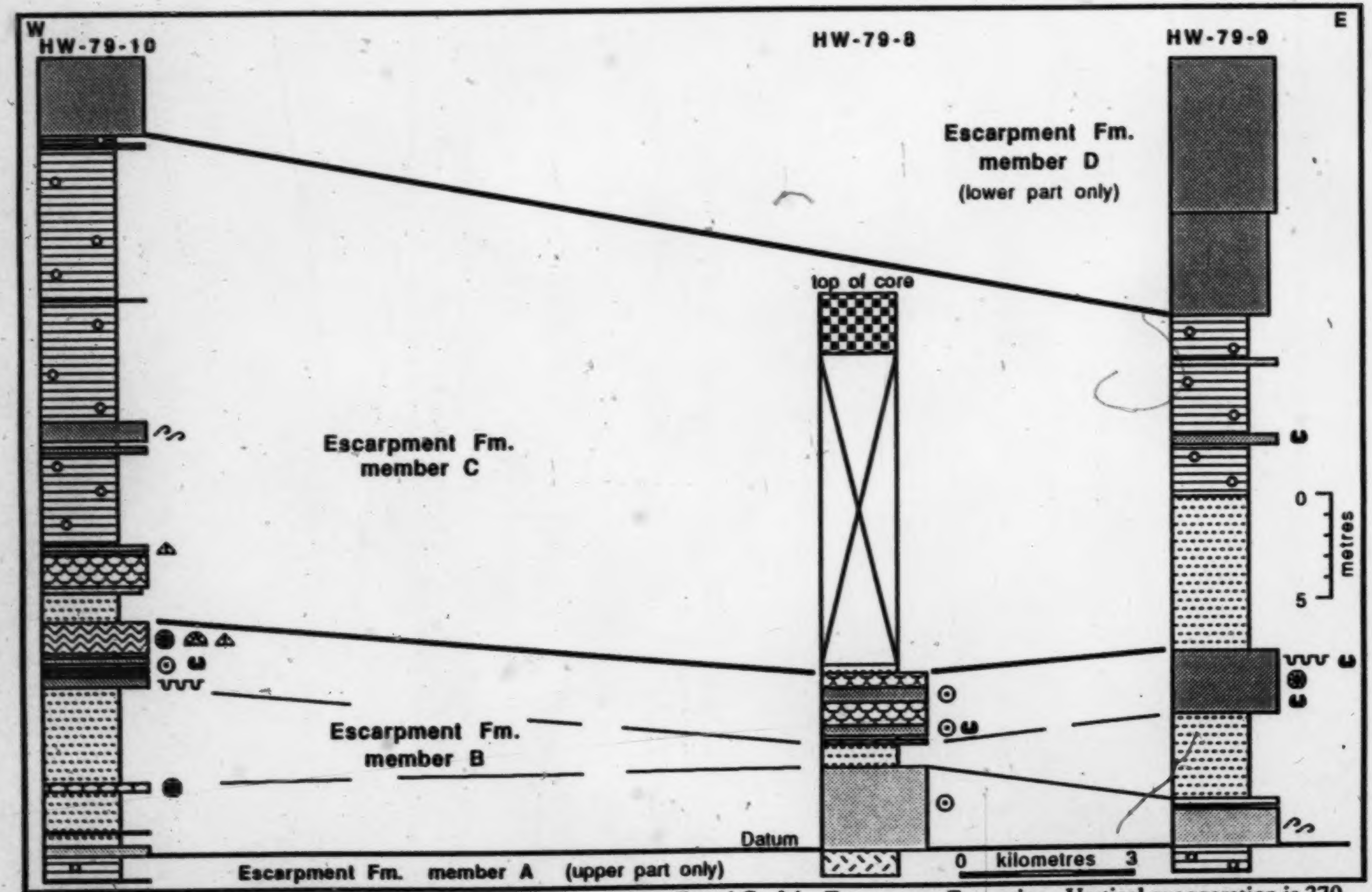


Figure 40. Part of cross section 4 showing correlation of members B and C of the Escarpment Formation. Vertical exaggeration is 370 times.

member B is resistant and weathers prominently (Plates 9B, 9C).

On geophysical logs the upper boundary of member B is placed at the top of a distinctive low gamma and neutron peak which corresponds to the thick resistant limestone unit at the top of member B (Fig. 12). Member B is recognizable on the logs by the presence of two, low gamma peaks separated by a shale interval with a high gamma count (Fig. 12).

Nature of contact

The contact between members B and C of the Escarpment Formation is relatively sharp throughout the study area. The nature of the contact is best observed in drill core. In outcrop the shales overlying member B are commonly slumped, making observation of the contact difficult.

Lithology

Member B consists of two thick, resistant units with a unit of recessive (Fig. 36) calcareous shale between them. The resistant unit at the base of the member consists of light to medium grey, finely planar to planar cross-laminated, unfossiliferous, calcareous siltstone to fine sandstone. In the field this unit weathers buff to orange brown. It is generally laminated to thinly bedded and, locally, contains asymmetrical ripple marks on its upper surface. Locally, such as at the base of HR-106, the sandstone exhibits rare thin argillaceous partings and laminations, erosional scour features and truncated beds and sharp walled, straight, vertical *Skolithos linearis* Haldeman (Plate 10A). Vertical burrows are commonly truncated by the overlying beds. The lithology of this unit changes locally from calcareous sandstone or siltstone to quartzose limestone (Figs. 39, 40). However, both lithologies retain the same physical sedimentary structures. The lithology changes from bed to bed and also from lamina to lamina.

The sandstone-siltstones, commonly contain between 55 to 60% detrtial quartz, 30 to 40% calcite, less than 5% dolomite, less than 2% muscovite and/or sericite, and minor amounts of pyrite (Plate 10B) and feldspar (microcline). Quartz generally occurs as 0.02 to 0.05 mm equigranular, subangular to subrounded grains. The calcite matrix, consisting mainly of 0.01

to 0.2 mm crystals, commonly contains 10 to 15% peloids, and 5 to 10% of highly abraded fossil fragments.

The quartzose unit at the base of member B is 0.5 to 3.8 m thick (average of 1.9 m) and maintains a relatively constant thickness from north to south (Fig. 39) but thins gradually toward the west, where, in HW-79-10, it is represented by a number of 10 to 50 cm thick, calcareous siltstone beds in shale (Fig. 40). The quartzose unit is overlain by a recessive unit consisting of green grey, calcareous shale (Figs. 39, 40). The shale unit is 1.0 to 4.5 m thick (average of 3.1 m). It thickens gradually toward the south and west (Figs. 39, 40).

The shale unit is overlain by a resistant limestone unit at the top of member B (Figs. 39, 40). The resistant unit consists of a number of thin to medium bedded limestones (Figs. 39, 40). In general, it consists of a basal, crinoidal packstone to grainstone and an upper, biostromal limestone, both of which are laterally discontinuous (Figs. 39, 40). The grainstone at the base of the unit was observed in sections HR-107 and HR-106 (Fig. 39) where it is an average of 1.45 m thick and consists mainly of crinoid ossicles with lesser amounts of brachiopod valves and gastropods, cemented by sparry calcite (Plate 10C). Locally, it contains 1 to 2 cm x 1 to 6 cm black bored limestone pebbles (Plate 10C) and smaller, 0.5 to 1 cm long oncoids. The grainstones commonly exhibit a crude, very thinly bedded appearance (Plate 10C). Locally, as in HW-79-10, hardgrounds are developed in these beds (Fig. 39). The bioclastic grainstone unit is sharply overlain by a biostromal limestone unit in sections HR-107 and HR-106 (Fig. 39).

The biostromal limestone consists of a matrix of light to medium grey brown, argillaceous wackestones to packstones. It can be characterized as a coral-stromatoporoid bindstone (Plate 10D). It contains abundant domal and platy corals, including *Phillipsastrea* sp. and *Alveolites* sp., encrusting *Aulopora* sp., solitary horn corals, encrusting, platy stromatoporoids and lesser amounts of brachiopods and crinoids (Plate 10D). Brachiopods collected from these beds, at a locality 39.8 m above the base of section HR-110, include *Calvinaria albertensis* (Warren), *Cyrtospirifer thalattodoxa* Crickmay, *Warrenella* sp., and

Cyrtina? sp. (written comm., B. Jones, 1986).

The wackestone to packstone matrix of the bindstones, occurs as pockets and lenses throughout the rock (Plate 10D). The matrix is commonly moderately bioturbated and slightly dolomitic, the dolomite being closely associated with burrows. Locally, 1 to 2 cm thick stromatoporoids and/or *Alveolites* sp. encrust the upper surfaces of the pockets and lenses. A well developed hardground occurs near the top of the biostromal unit at section HR-106 (Fig. 39).

In the biostromal unit, 1 to 30 cm thick lenses of bioturbated fossiliferous packstone to grainstone occur locally. These contain abundant abraded fragments of *Thamnopora* sp. and other corals, stromatoporoids, brachiopods and crinoid ossicles.

The biostromal unit has a rubbly appearance in outcrop and core (Plate 6C) due to the differential weathering of the argillaceous matrix and the more resistant allochems. In addition, burrow fills in the wackestones and packstones are commonly less argillaceous and more indurated than the more argillaceous matrix. The biostromal unit is 1.2 to 5.3 m thick (average of 3.1 m). In general, it thins toward the south and west (Figs. 12, 39, 40). Locally, where the biostromal unit is absent, as at HW-79-8 and HW-79-9, the equivalent beds comprise intensely to completely bioturbated, light to medium grey brown, fossiliferous wackestones to packstones (Plate 10E). These beds have a nodular appearance due to the differential weathering of argillaceous matrix and more indurated burrow fills (Plate 10E) and are variably quartzose and commonly contain abundant bored and unbored black pebbles (Fig. 40; Plate 10E).

Thickness and distribution

Member B is 7.9 to 10.9 m thick. In general, it thickens gradually toward the south and west (Figs. 12, 39, 40).

H. Member C

Introduction

In the reference section HW-79-9 the 15.5 m (59.4 to 44.0 m) of green grey, calcareous shale, calcareous shale with limestone nodules (Plate 10F) and thin beds of argillaceous to quartzose limestone, overlying member B and underlying grey brown limestones, is herein referred to member C of the Escarpment Formation (Fig. 36). The definition of this member differs from that of the corresponding member D of the Hay River Formation by Jamieson (1968).

Upper boundary

In the reference section the upper boundary of member C is placed at the contact between greenish grey, fissile to blocky, calcareous shale with argillaceous limestone nodules and massive, thin to medium bedded, grey brown argillaceous limestone (mudstone to wackestone) at the base of member D (Fig. 36). This contact is well exposed in drill core from HW-79-9 and HW-79-10. In outcrop the contact is exposed at the base of section HR-108 at the base of the lower falls on Twin Falls Creek (Plate 11A), and near the top of section HR-107 (Plate 9E; Fig. 39). The upper boundary of member C is easily recognizable in the field because it occurs at the base of the massive cliff forming limestones of the overlying member D (Plates 9C to 9E, 11A, 11E). This boundary probably corresponds to the definitions of the top of the Hay River shale by Cameron (1918) and the Hay River Formation by Crickmay (1953).

The placement of the upper boundary of member C differs from Jamieson's (1968) definition of the corresponding member D of the Hay River Formation. Jamieson (1968, Fig. 4) showed a biostromal limestone unit at the top of her member D. She measured this unit in outcrop at a section on Hay River near Enterprise, at the junction of the Mackenzie and Hay River Highways. She placed the upper boundary of member D at the top of a 0.48 m (1.6 ft) thick coral-stromatoporoid bindstone, dominated by encrusting *Alveolites* sp. and stromatoporoids and lesser amounts of brachiopods and solitary corals. She noted that this unit overlies a 1.1 m (3.6 ft) thick crinoidal packstone and a 0.83 m (2.7 ft) thick argillaceous skeletal wackestone. These beds apear to be the same as the resistant unit measured near the top of section HR-104 (Fig. 39), in this study. However, this bed probably correlates with beds in member C, farther upstream at sections HR-105 and HR-107, below the massive cliff forming limestones of the overlying member D of the Escarpment Formation (Fig. 39).

Jamieson (1968) noted that her member D of the Hay River Formation is overlain by a 1.5 m (5 ft) thick, covered interval which she presumed to comprise silty, green grey shale. Therefore, the definition of the upper boundary of member C of the Escarpment Formation lies 4.5 to 5.5 m above the upper boundary of the corresponding member D of the Hay River Formation as defined by Jamieson (1968).

On geophysical logs the upper boundary of member C of the Escarpment Formation is placed ~~at the base of a~~ relatively low and high neutron "kick" (Fig. 12). This corresponds to the limestone unit comprising the overlying member D. The log profile of this part of the section is somewhat anomalous, however, because of the increased amplitude of the gamma and neutron responses due to the presence of casing in the upper part of the holes (Fig. 12).

Nature of contact

In drill core and outcrop the contact between the shales of member C and the thinly bedded limestones of member D, is sharp. The contact is readily identifiable in outcrop due to the contrast in weathering patterns of the different lithologies. The shales of member C are recessive and form soft talus or slumped covered sections beneath the cliff forming limestones of member D (Plates 9C to 9E).

Lithology

Member C consists mainly of green grey, calcareous, fissile shale and calcareous shale with argillaceous limestone nodules (Plate 10F). In general, the shales of member C are fissile to blocky, with compositions approaching calcareous mudrock. Limestone nodules occur primarily in the shales toward the upper part of the member (Fig. 39), however, toward the west they commonly occur throughout the shales (Fig. 40). Although the nodules consist mainly of argillaceous mudstones they locally contain abundant skeletal fragments. In some cases they contain spar filled fractures (Plate 10F). Locally, such as at section HR-104, the shales above member B are mottled maroon and grey in colour. The shale unit is 4.5 to 9.5 m thick, with an average thickness of 7.4 m.

A number of resistant beds, 0.10 to 1.2 m thick, occur in the upper part of member C (Fig. 39; Plates 9D, E). These beds are variable in composition and include argillaceous mudstones to wackestones, fossiliferous packstones to grainstones, quartzose limestones and, locally, coral-stromatoporoid bindstones.

Toward the middle part of member C there is a 0.5 to 1.2 m thick (average of 0.85 m) limestone unit (Fig. 39; Plates 9D, E) that consists of light to medium brown grey, intensely to completely bioturbated, fossiliferous, slightly dolomitic, argillaceous wackestone to packstone. It commonly contains dark rimmed to black, bored and unbored pebbles (Plate 11C; Fig. 39). Dolomite is confined mainly to burrow fills. A similar resistant limestone bed occurs near the top of section HR-104 (Plate 11B). There, however, the limestone unit consists of a basal 0.5 m of fossiliferous, quartzose limestone overlain by 1.2 m of argillaceous, fossiliferous, crinoidal packstone to grainstone (Plate 11D). The packstone to grainstone unit is capped by a 0.5 m thick biostromal unit (Plate 11B) consisting of platy *Alveolites* sp. and stromatoporoids and some *Thamnopora* sp. fragments, rugose corals (*Macgeea* sp., *Tabulophyllum* sp.) and scattered brachiopods. Mitchell (1970) noted that the brachiopods in this bed include *Emanuella* sp., *Cyrtospirifer* sp., *Cyrtina* sp.,and *Schizophoria*. sp. The matrix of the bindstones consists of light to medium grey brown to olive brown, slightly to moderately bioturbated, fossiliferous mudstone to wackestone. The biostromal unit at the top of section HR-104 appears to be laterally discontinuous since it was not detected in any of the adjacent measured sections or cores (Fig. 40). Therefore, the biostromal unit is probably a localized facies within the relatively thick limestone unit near the middle of member C.

In the shales above this resistant limestone unit (Fig. 39), a number of thin limestone beds occur. They are variably quartzose, argillaceous and fossiliferous and range from massive mudstones to intensely bioturbated wackestones to packstones. The uppermost of these beds, in sections HR-107 and HW-79-9, consists of finely planar laminated, quartzose limestone (mudstone) with some cross cutting vertical to subvertical, sharp-walled burrows. The beds in the upper part of member C become more difficult to correlate toward the west (Fig. 40).

Thickness and distribution

Member C is 9.6 to 33.8 m thick. In general, it thins gradually toward the south and thickens toward the west (Figs. 39, 40).

I. Member D

Introduction

In the reference section HW-79-9 the 14.6 m (44 to 29.4 m) of thin to medium bedded, variably argillaceous, light to medium grey brown limestones, overlying shales with thin interbeds of limestone in member C, are herein referred to member D of the Escarpment Formation (Fig. 36). The section immediately overlying the limestones of member D was cored, but was not recovered (Fig. 36). As a result, the upper boundary of the member could not be accurately placed. However, based on evidence from other cores and outcrop, the missing unit was probably composed of recessive shale. It is assumed, therefore, that the top of the limestone in HW-79-9 probably represents the top of member D.

The most distinctive feature of member D is its massive cliff forming nature in the field (Plates 9C to E, 11A, E, 12A, B). Based on interpretations of aerial photographs and measured section correlations, the cliff section formed by the limestones of member D could be traced from Twin Falls, downstream along the banks of Hay River, to a point southwest of Enterprise (Fig. 41). As noted by Jamieson (1968) this limestone unit probably forms the cliff section below Escarpment Lake. The upper cliff section at Twin Falls Creek (Plate 6B), formed by member E of the Escarpment Formation and the overlying Twin Falls Formation, sits back farther from the banks of the river and forms an escarpment which swings toward the

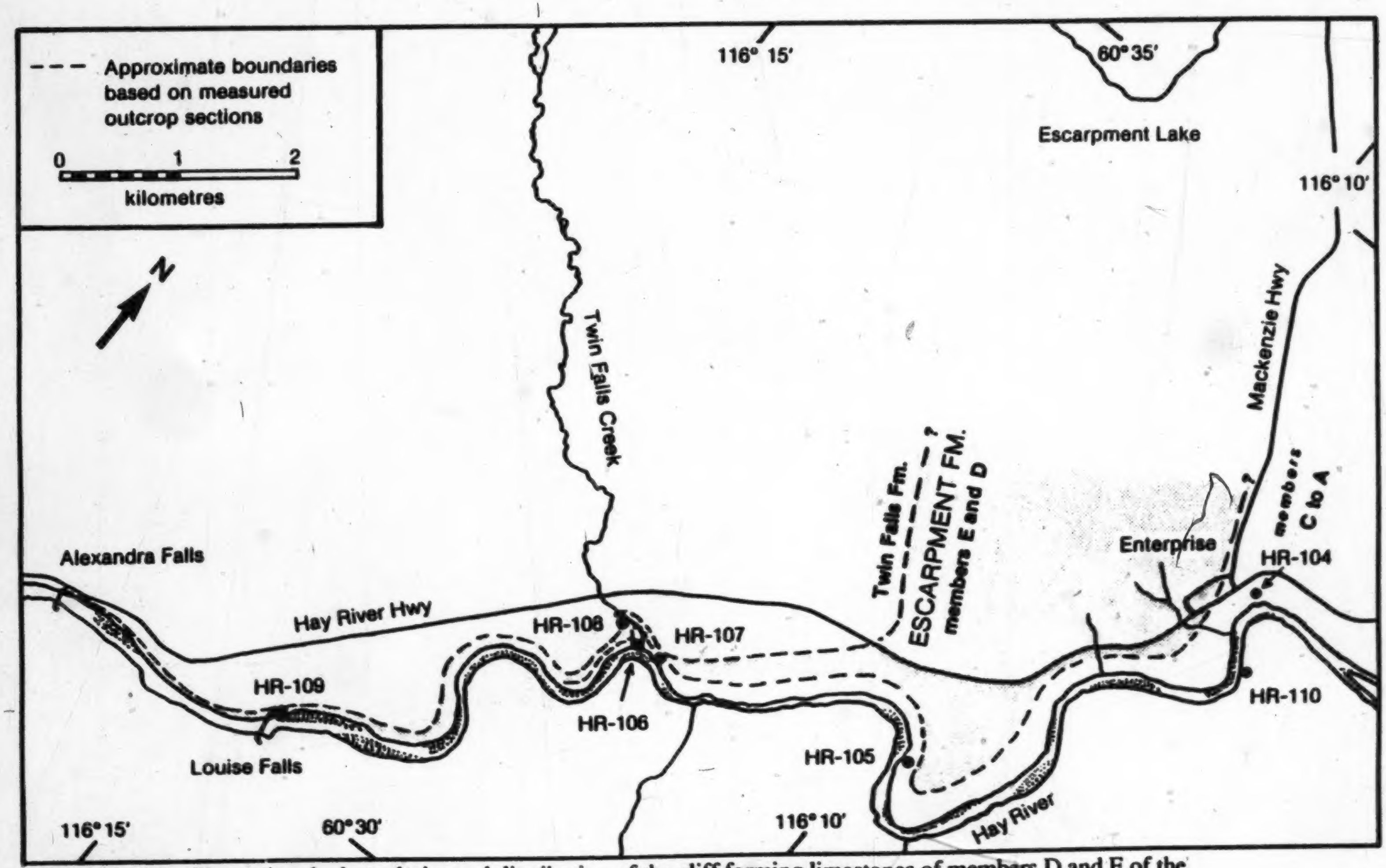


Figure 41. Map illustrating the boundaries and distribution of the cliff forming limestones of members D and E of the Escarpment Formation and the overlying Twin Falls Formation (adapted from Jamieson, 1968).

north, at a point approximately 2.5 km to the northeast of Twin Falls Creek (Fig. 41). Jamieson (1967, 1968) traced this section toward the north to the cliff sections below Heart Lake. The placement of the boundaries of member D of the Escarpment Formation differs from the definition of the corresponding member E of the Hay River Formation by Jamieson (1968).

Upper boundary

At section HR-108, the upper boundary of member D is placed at the top of the lower falls on Twin Falls Creek (Fig. 42; Plate 11A). There the upper boundary is placed at the top of a 1.3 m thick, resistant limestone bed which forms the top of the lower falls (Plate 11A). This unit provides a useful marker because of its resistant weathering pattern. It forms a cap-like unit at the top of member D which can be traced along the cliff section along Hay River from section HR-107 (Plate 9E) upstream to section HR-106 (Plate 9C) to section HR-109, where it forms the top of Louise Falls (Plates 12A, B).

The placement of the upper boundary of member D at the top of this bed differs from the definition of the upper boundary of the corresponding member E of the Hay River Formation by Jamieson (1968). The upper boundary of member E was placed by Jamieson (1968) at the top of a 2.1 m (7 ft) thick biostromal limestone unit near the top of the lower falls on Twin Falls Creek (Fig. 42). She traced this unit to Louise Falls. As measured in this study at section HR-108, the biostromal unit occurs 2.6 m below the top of the resistant unit which caps the top of the lower falls (Fig. 42; Plate 11A). The limestones above and below the biostromal unit are similar in composition and should be included with it in member D (Plate 11A).

At the top of the lower falls, the resistant limestone unit which caps the falls, is overlain by a thin, recessive, argillaceous limestone unit (Fig. 42). This unit forms the base of the overlying member E of the Escarpment Formation. The contact between the two members is not observable because the basal part of member E is recessive and commonly covered. The recessive nature of the basal part of member E is best seen on the southeast side of Hay River

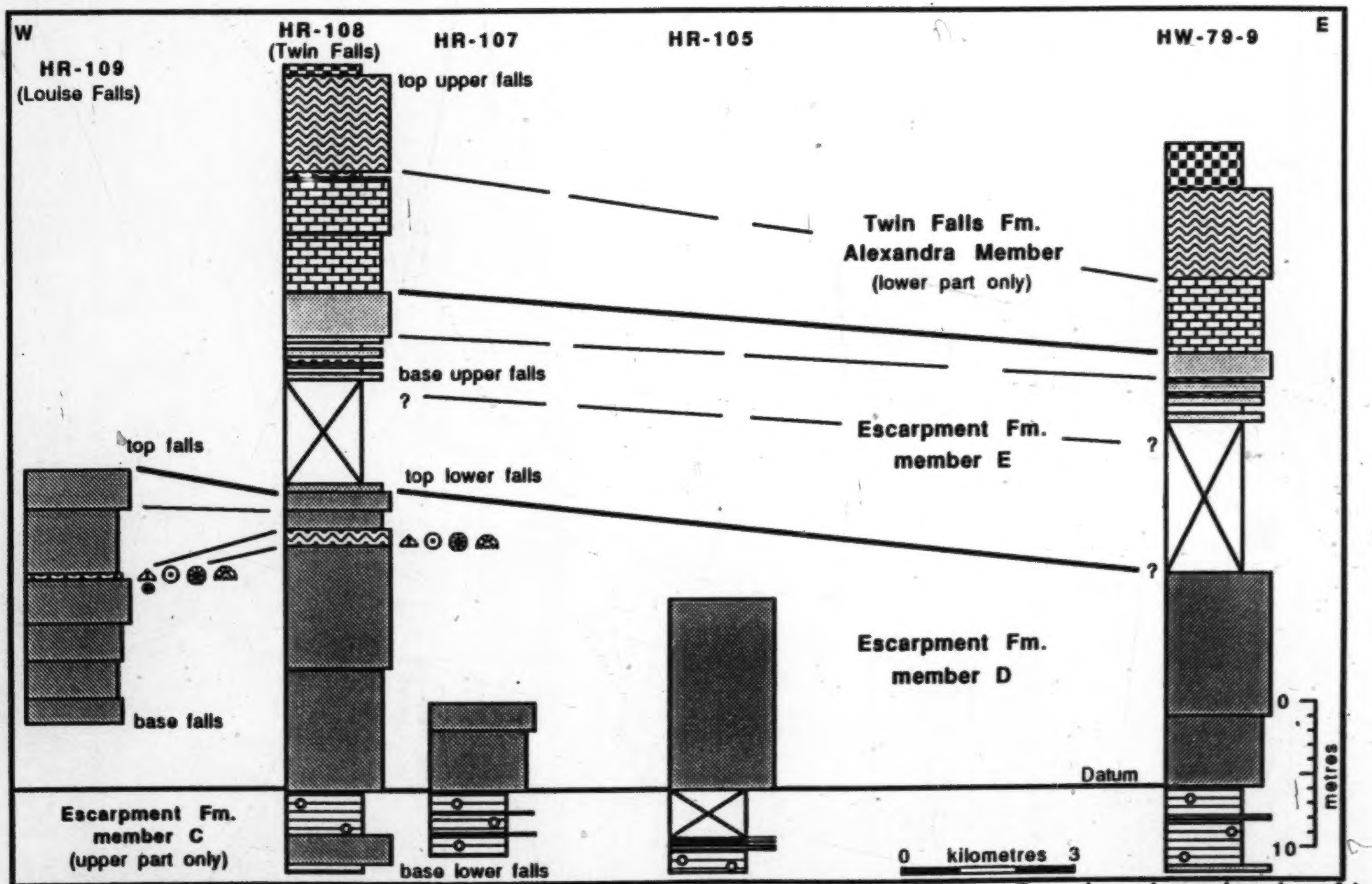


Figure 42. Part of cross section 1 illustrating correlation between members D and E of the Escarpment Formation and upper boundary of the Escarpment Formation with the overlying Alexandra Member of the Twin Falls Formation. Vertical exaggeration is 250 times.

across from Louise Falls (Plate 12B). The recessive covered interval is presumed to comprise green grey calcareous shale, because: (1) a unit of calcareous shale overlies the limestones of member D in HW-79-10 (Fig. 43), (2) in outcrop, the unit overlying member D is recessive and commonly covered (Plate 12B), (3) a thin unit of recessive calcareous shale to mudrock, with thin interbeds of argillaceous, calcareous sandstone is exposed at the base of the upper falls on Twin Falls Creek (Plate 6B; Fig. 42), and (4) a recessive shale unit above member D is recognizable on geophysical logs by its high gamma and low neutron counts (Fig. 12).

On geophysical logs the upper boundary of member D is placed at the top of a low gamma and high neutron "kick" (Fig. 12). This kick corresponds to the resistant limestone which forms member D. The log profile changes to much higher gamma and lower neutron values above this point, corresponding to the recessive shales at the base of member E (Fig. 12).

Nature of contact

The contact between limestones at the top of member D and recessive limestone or shale at the base of member E ranges from gradational to sharp. This contact occurs at the top of the lower falls on Twin Falls Creek (section HR-108) and in the core from HW-79-10 (Fig. 43). Locally, such as at HW-79-10, the shales at the base of member E contain a number of 1 to 2 cm thick, argillaceous limestone beds, however, these are considered to be part of the recessive unit at the base of member E.

Lithology

Member D consists mainly of thin to medium, parallel bedded, light to dark grey brown or brown, variably argillaceous mudstones to wackestones. Commonly the limestone beds are separated by 1 to 10 cm thick interbeds of calcareous shale to very argillaceous limestone. These weather recessively and enhance the bedded appearance of the limestones (Plates 11A, 12A to D). The limestone beds are locally undulose to wavy, parallel bedded (Plate 12D). In outcrop the limestones weather with a characteristic flaggy appearance (Plate 11A). The limestones, which are predominantly slightly to highly bioturbated, mudstone to

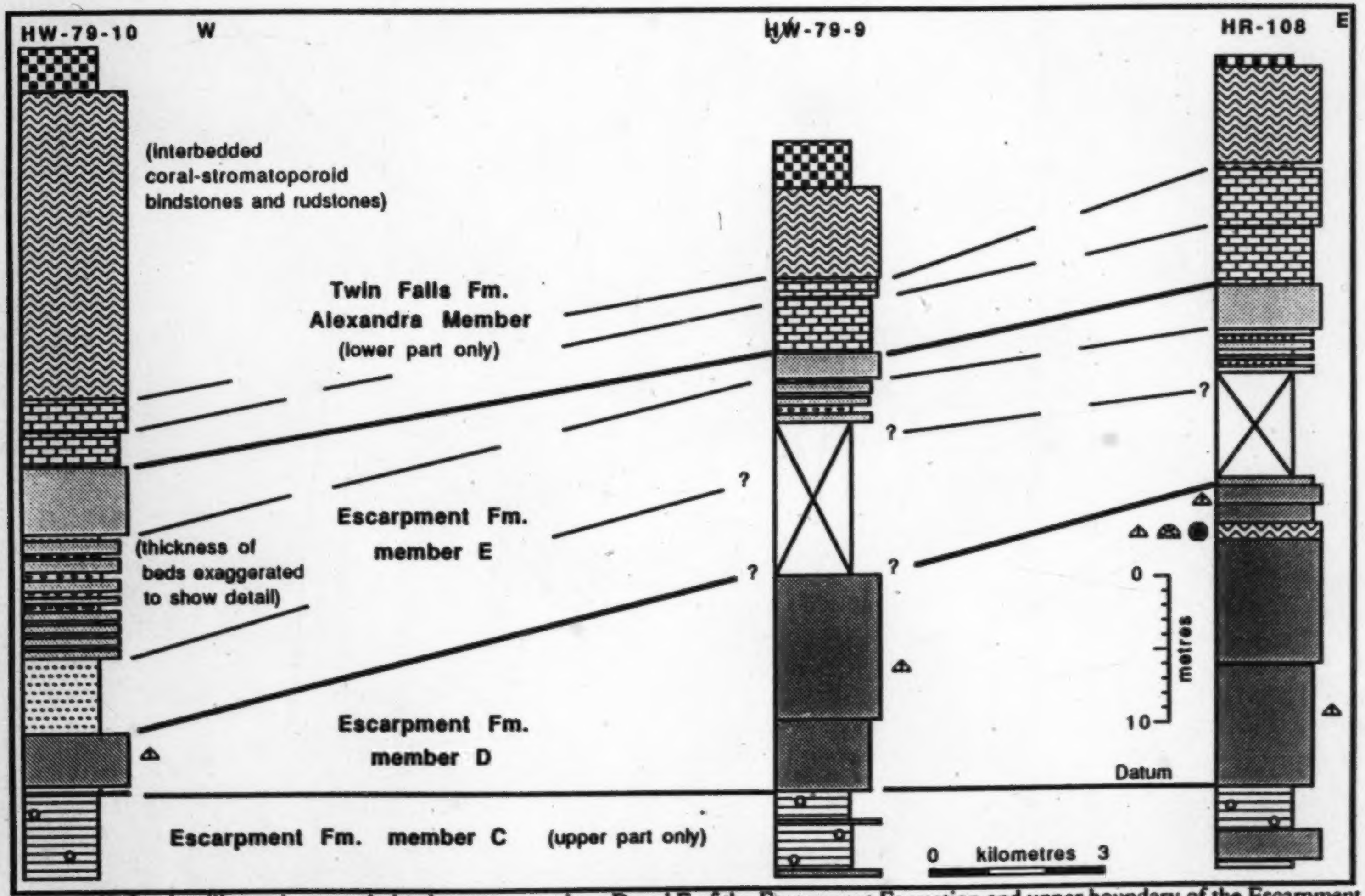


Figure 43. Section illustrating correlation between members D and E of the Escarpment Formation and upper boundary of the Escarpment Formation with the overlying Alexandra Member of the Twin Falls Formation.

wackestone commonly have a nodular appearance due to the presence of light coloured burrow fills and dark brown wispy seams (Plate 13A). Light coloured mudstone nodules are commonly cross cut by spar filled fractures (Plate 13A).

Locally, some beds contain from 10 to 30% allochems, consisting mainly of disarticulated and articulated brachiopods, gastropods, crinoid ossicles and ostracodes. Rugose corals, mainly *Macgeea* sp., occur throughout the section. Articulate brachiopods are commonly filled with coarsely crystalline calcite and in some cases, geopetal structures are preserved. Commonly, skeletal material has been replaced by coarse calcite. Brachiopods collected from 2.3 m above the base of section HR-109 include *Atrypa* sp., *Devonoproductus* sp. and *Eleutherokomma* sp. (written comm., B. Jones, 1986). Burrows are commonly represented by vague or indistinct mottles, however, *Chondrites* sp. and *Teichichnus* sp. are locally well preserved (Plate 13B). The matrix of the limestones consists primarily of micrite, with lesser amounts of fine fossil hash, microspar, and idiotopic-porphyrotopic dolomite and argillaceous material. Dolomite most commonly occurs in close association with burrows. Locally, peloids are a common component of the limestones.

Detrital quartz and pyrite are ubiquitous components of the limestones. The proportion of quartz is variable, ranging from 0 to 20%, but generally form less than 3 to 5% of the rocks. The quartz is equigranular and occurs as 0.01 to 0.04 mm, subangular to subrounded grains. The average size of the grains is approximately 0.025 mm. Pyrite forms less than 2 to 3% of the limestones. It occurs most commonly as 0.005 to 0.01 mm crystals, disseminated throughout the rock or, as larger, 0.05 to 1.0 mm crystals or aggregates of crystals. Pyrite is closely associated with argillaceous and/or organic material and burrows and, commonly, has partially replaced skeletal fragments and calcite cements.

Most of member D consists of lithologically homogeneous limestones, however, near the top of the member, a number of different lithologies are present. At section HR-108 (Fig. 42) a 1.1 m thick biostromal unit occurs 16.6 m above the base of member D (Plate 11A). Jamieson (1968) determined the thickness of the unit, at Twin Falls Creek, to be 1.7 m (5.5 ft) thick, however, the biostromal unit thins and thickens locally and she may have measured the unit at a different position at this locality. She suggested that the biostromal unit thickens toward the river to 5.5 m (18 ft). The thickening of the unit in this direction is evident at the top of the cliff section at HR-107 where the biostromal limestone can be seen underlying the resistant capping unit at the top of member D (Plate 9E). The exact thickness of the unit could not be determined, however, because of the steepness of the cliff section.

This biostromal unit consists mainly of coral-stromatoporoid bindstone. In comparison to the bindstones in the underlying members of the Escarpment Formation, which consist mainly of tabular and encrusting forms of corals and stromatoporoids, the biostomal unit in member D contains a greater diversity of relatively more massive forms. In addition, it contains a higher ratio of binding allochems to fine matrix. The main binding organisms are *Alveolites* sp. and stromatoporoids (Plate 13C). The matrix is commonly fossiliferous wackestone to packstone and contains thin shelled brachiopods, crinoid ossicles, ostracodes and fragments of *Thamnopora* sp. and rugose corals. The matrix is slightly to moderately bioturbated, however, recognizable burrows are rarely preserved. Bioturbated portions of the rock are commonly dolomitized. The dolomite is ferroan, and occurs as idiotopic euhedral to subhedral crystals with an average size of 0.03 mm. At Twin Falls Creek this biostromal unit is overlain by a more recessive limestone unit (Plate 11A; Fig. 42).

At Louise Falls (Fig. 42), a similar biostromal unit forms a resistant ledge approximately 9.7 m above the base of the falls (Fig. 42; Plates 12A, 13D). This unit varies in thickness, along this exposure, from 0.4 to 0.8 m and has gradational upper and lower contacts. It consists mainly of platy to low domal forms of *Alveolites* sp., *Phillipsastrea* sp. and other corals (Plate 13D), stromatoporoids, horn corals (*Macgeea* sp., *Tabulophyllum* sp.), brachiopods (including *Spinatrypa* sp., *Cyrtospirifer* sp., *Atrypa* sp., strophomenid indet.), crinoid ossicles, bryozoans and gastropods. Black pebbles occur locally. Commonly the areas between the corals and stromatoporoids are filled with an argillaceous, fossiliferous packstone to floatstone matrix, consisting of horn corals and abraded brachiopod valves, gastropods and bryozoans (Plate 13E). These rocks are commonly moderately bioturbated and dolomitic.

There is some discrepancy regarding the thickness of the biostromal unit at Louise Falls. Belyea and McLaren (1962) and Stearn (1966) noted the presence of this unit at Louise Falls. Belyea and McLaren (1962) suggested that the biostromal unit is 4.9 m (16 ft) thick and forms Louise Falls. This disagrees with the thickness determined for this unit here. It is possible, however, that they included the resistant limestone unit which forms the top of Louise Falls (Plate 12A) in their measurements. This resistant capping unit contains abundant rugose corals (Plate 14A) and some colonial corals and stromatoporoids, however, it is not biostromal and is separated from the thin biostromal unit near the middle of the falls (Plates 12A, B, 13F) by a 4.3 m thick, recessive, argillaceous limestone unit. Therefore, it was not included with the biostromal unit near the middle of the falls.

At Louise Falls the resistant biostromal unit near the middle of the falls (Plate 12A) is overlain by 4.3 m of relatively recessive, thinly bedded, argillaceous mudstones to wackestones (Fig. 42; Plates 12A, 13F). The limestones are generally unfossiliferous, however, thin shelled brachiopods and rugose corals occur throughout the section. The limestones become more massive toward the top of the unit (Plate 13F). The limestone beds are separated by 1 to 5 cm thick interbeds of calcareous shale to very argillaceous limestone. Commonly the limestone beds have a nodular, rubbly weathered appearance (Plate 13F), due to localized pinching and swelling of the beds and the differential weathering of the shaley interbeds.

The recessive, thinly bedded limestone unit is overlain by a 2.3 m thick, resistant limestone unit which forms the top of Louise Falls (Fig. 42; Plates 12A, B, 13F). The resistant capping unit appears to be the same unit which forms the top of the lower falls on Twin Falls Creek (Fig. 42; Plate 6B). At Louise Falls this unit consists of light to medium grey brown, fossiliferous packstone to rudstone. Allochems consist mainly of rugose corals (*Macgeea* sp., *Tabulophyllum* sp.), some platy *Alveolites* sp. and stromatoporoids, brachiopods (*Atrypa* sp., *Cyrtospirifer thalattodoxa* Crickmay, *Cyrtina* sp. and strophomenid indet.), crinoid ossicles and rare crinoid holdfasts (Plate 14A). The matrix of the rock consists primarily of micrite with patches of coarse crystalline calcite and dolomite. This unit is slightly to moderately bioturbated, with unidentified burrows preserved in concave and convex epirelief (Plate 14A). This resistant capping unit is overlain by a recessive covered interval at the top of Louise Falls, corresponding to the recessive unit at the base of Member E of the Escarpment Formation (Plate 12B).

At section HR-108, near the top of the lower falls on Twin Falls Creek, the biostromal unit is gradationally overlain by a relatively recessive, 1.2 m thick, thinly bedded, flaggy weathering, argillaceous limestone unit (Fig. 42). This unit is lithologically similar to the limestones underlying the biostromal unit (Plate 11A). The recessive limestone unit is sharply overlain by a resistant, ledge forming limestone unit (Fig. 42; Plate 11A).

The resistant limestone bed at the top of the lower falls, at Twin Falls Creek, has a subtle flaggy weathered appearance, however, it is generally more massive and indurated than the underlying limestones. It consists of light to medium grey brown to brown, peloidal, fossiliferous wackestone to packstone. The matrix of the rock is very fine grained, consisting mainly of micrite, with rare patches of neomorphic calcite spar (crystals 0.05 to 1.0 mm across). Allochems consist mainly of abraded brachiopod valves, small gastropods, bryozoans, ostracodes, foraminifera, and crinoid ossicles. A number of species of foraminifera (*Neogenus* sp. and *Nanicella* sp.) occur in the limestones of member D (pers. comm., T. Marchant, 1986). The limestones are slightly to moderately bioturbated with *Teichichnus* sp. preserved locally. In some places the limestones grade vertically into slightly quartzose, dolomitic, fossiliferous wackestone to packstone.

The resistant capping unit is overlain by approximately 0.7 m of recessive, grey brown, argillaceous wackestone. It is slightly bioturbated and contains some brachiopods and crinoid ossicles. The upper boundary could not be accurately determined, however, it was included in the overlying member E of the Escarpment Formation because of its argillaceous and recessive nature. It is overlain by a 7 m thick, recessive covered interval (Fig. 42).

Thickness and distribution

Member D is 4.2 to 21.0 m thick. Based on observations of the cliff sections, exposed along the banks of Hay River from section HR-105 upstream to Louise Falls, the member appears to maintain a relatively constant thickness from the northeast to southwest (Fig. 42). Toward the west, however, the member thins to approximately one fifth of the thickness at Hay River. In general, two observations could be made regarding the character and distribution of the member: (1) the limestones comprising member D become more argillaceous and recessive toward the south and west, and (2) biostromal beds in the member thin toward the south and are absent toward the west, in the subsurface.

J. Member E

Introduction

The lower part of member E was not recovered in the reference section HW-79-9 (Fig. 36). Therefore, core from HW-79-10 is herein designated as the reference section of member E of the Escarpment Formation. In HW-79-10, the 5.0 m of green grey, calcareous shale and the overlying 11.5 m of interbedded calcareous shale and argillaceous sandstone and medium bedded, laminated sandstone-siltstone are herein referred to member E of the Escarpment Formation (Fig. 43). In HW-79-10, member E occurs between the depths of 46.2 and 28.4 m. Member E is underlain by massive bedded limestone of member D and overlain by buff coloured limestones and dolomitic limestones of the Alexandra Member of the Twin Falls Formation (Figs. 42, 43).

Upper boundary

In HW-79-10 the upper boundary of member E, which occurs at a depth of 28.4 m, is placed at the contact between light to medium green grey, planar to cross-laminated, medium bedded, calcareous to dolomitic, sandstone-siltstone and buff to light brown, stylolitic, variably quartzose, limestone and dolomitic limestone at the base of the Twin Falls Formation (Figs. 36, 43). In HW-79-9 the contact occurs at a depth of 14.3 m. This contact is well exposed in drill core and in outcrop at the base of the upper falls (Fig. 42) on Twin Falls Creek

(Plate 6B). It is also well exposed at Louise and Alexandra Falls, however, it was not measured at these localities. The lithology of the rocks at this contact is relatively consistent throughout the study area. The placement of the upper boundary of member E of the Escarpment Formation corresponds to the definition of the top of the Hay River Formation by Crickmay (1957) and the top of the Escarpment Member of the Hay River Formation by Belyea and McLaren (1962).

On geophysical logs the upper boundary of member E of the Escarpment Formation is placed at the change from moderate gamma values of the calcareous sandstone-siltstones at the top of member E to the flat, low gamma count profile of the clean carbonates at the base of the Alexandra Member (Fig. 12). There is a corresponding increase in the neutron count, to higher values in the carbonates of the Twin Falls Formation (Fig. 12). The log response for member E indicates the presence of a shale interval at the base of member E (Fig. 12). In general, the argillaceous content of the rocks in member E decreases toward the top of the member as indicated by a decrease in the gamma count in this direction (Fig. 12).

Nature of contact

In drill core and outcrop the contact between member E of the Escarpment Formation and the Alexandra Member of the Twin Falls Formation is sharp and apparently conformable. The contact is readily identifiable in drill core due to the contrast in colour of the unweathered rocks. In outcrop this difference is masked by the weathered nature of the rocks. However, the contact can be recognized by the change in bedding character between the two. The calcareous sandstones at the top of member E are medium bedded and weather in a blocky manner (Plate 6B). In contrast, the carbonates at the base of the Alexandra Member are thinly bedded and have a flaggy weathered appearance (Plate 6B).

Lithology

Member E consists mainly of calcareous shale and calcareous to dolomitic, quartzose sandstone-siltstone. In the reference section for member E, HW-79-10 (Fig. 43), a 5 m thick unit of shale overlies massive limestones of member D and is overlain by a transitional unit of thinly interbedded calcareous silty shale and calcareous sandstone-siltstone (Plate 14B). The shale unit consists of medium green grey, fissile, calcareous shale with some thin (less than 2 cm thick) argillaceous limestone beds. It is 5 to 15 m thick (average of 9 m) but thins toward the south and thickens toward the west.

In HW-79-10 the transitional unit (Fig. 43) consists of thinly interbedded calcareous, silty shale and calcareous to dolomitic, laminated, argillaceous sandstone-siltstone and, locally, quartzose limestone. The sandstone-siltstones occur as laminae within the shale or, as 1 to 10 cm thick, wavy parallel beds (Plate 14B). The interbedded lithologies of this unit are commonly slightly bioturbated. In HW-79-10 the transitional unit is 8.4 m thick (Fig. 43). The upper part of this unit (3.0 m) is exposed at section HR-108, at the base of the upper falls on Twin Falls Creek (Plate 6B). The transitional unit is recognizable on geophysical logs by gamma-ray profiles with API values midway between those of the calcareous shale below and the calcareous sandstone-siltstones above (Fig. 12).

The transitional unit is overlain by medium green grey to grey, medium bedded, variably calcareous and dolomitic, thinly planar to low angle cross-laminated, sandstone-siltstone (Plate 5F). This quartzose unit is well exposed in outcrop due to its resistant, prominent weathered appearance (Plate 6B). In general, this unit is variable in composition. Quartz is ubiquitous but varies in proportion from lamina to lamina and bed to bed. The rocks range in composition from quartzose dolomitic limestones and calcareous dolostones to sandstone-siltstone with less than 5% calcite and/or dolomite cement.

The laminated appearance of the rock is enhanced by compositional differences between laminae. Laminae rich in calcite and dolomite are light coloured, whereas, those rich in quartz are darker coloured (Plate 14C). Argillaceous laminations are commonly medium grey green in colour. Organic and argillaceous material is commonly associated with the quartzose laminae, accentuating the dark colouration. Locally, the sandstones contain 0.1 to 0.5 cm thick argillaceous siltstone to calcareous, silty shale stringers (Plate 14B).

Quartz occurs as 0.005 to 0.15 mm, monocrystalline, angular to subrounded, equidimensional to elongate grains. The majority of the grains are equidimensional (Plate 14C). Feldspar (microcline) grains, muscovite and/or sericite laths, pyrite, and argillaceous and organic material and generally form less than 1% each of the rock. Calcite and dolomite occur mainly as cements which have filled the pore spaces between quartz grains. The cements commonly contain inclusions of detrital quartz. Locally the sandstone-siltstone and quartzose limestones contain abundant peloids. These are an average of 0.05 mm in size and consist of dark brown microcrystalline calcite (Plate 14D). Fine, abraded fossil fragments are locally abundant (less than 5%) and occur throughout the matrix of the rocks. They are commonly less than 0.1 mm in size and consist of fragments of brachiopods, ostracodes and crinoid ossicles.

The sandstone-siltstones are commonly slightly to moderately bioturbated. Locally they have been intensely bioturbated, with only minor vestiges of original sedimentary structures preserved. Burrows are commonly vertically oriented and are represented by traces of *Skolithos* sp., *Planolites* sp. and *Chondrites* sp., which commonly show signs of deformation (Plates 5F, 14E), possibly indicating thixotropic conditions in the sediment at the time of burrowing. Burrows have commonly been truncated by overlying beds; however, some beds contain traces with sharp outlines and, locally, scratch marks made by possible arthropod appendages. These are indicative of burrowing in a firm substrate. Slabs collected from the base of outcrops of the sandstone unit at the top of member B at Louise and Twin Falls contained traces of *Diplocraterion* sp., *Uchirites* sp., *Trichophycus* sp., *Planolites* sp. (Plate 15A) and *Scolicia* sp. (Plate 15B) preserved in epirelief on the upper surfaces of bedding planes (Plates 15A and B). Locally, some beds have a nodular appearance due to the differential weathering of the matrix and the burrow fills. Burrows fills are commonly finer grained, less argillaceous and more indurated that the surrounding matrix and, as a result, weather more prominently.

The sandstone-siltstone unit ranges in thickness from 3.0 to 4.4 m, with an average thickness of 3.5 m. In general, it maintains a relatively uniform thickness in the sections examined.

Thickness and distribution

Member E of the Escarpment Formation is 13.5 to 29.0 m thick. It thickens toward the west and maintains a relatively constant thickness from north to south (Figs. 12, 43).

VIII. TWIN FALLS FORMATION

A. Introduction

In the reference section HW-79-9, the buff to light brown, variably quartzose limestones and dolomitic limestones overlying green grey calcareous sandstone-siltstone at the top of the Escarpment Formation are referred to the Alexandra Member of the Twin Falls Formation (Fig. 36). These units grade upward into fossiliferous, dolomitic bindstones and floatstones (Plates 15C, D). The base of the Alexandra Member occurs at a depth of 14.3 m in the reference section HW-79-9. Only the lower part of the Alexandra Member was examined in this study. The type section of the Twin Falls Formation and Alexandra Member is located at Alexandra Falls (Plate 15E) on Hay River (Crickmay, 1957; Belyea and McLaren, 1962).

B. Lithology

In HW-79-9, HW-79-10 and section HR-108, the basal unit of the Alexandra Member consists of thinly bedded, buff to light brown, quartzose, dolomitic, mudstone to wackestone (Plate 6A). These rocks have a slightly nodular appearance due to the presence of numerous dark brown, organic rich, "horse tail" seams (Plate 6A) and the effects of intense bioturbation. The "horse tail" seams are commonly stylolitic (Plate 6A). Allochems,which form less than 10 to 15% of the rock, consist of small, thin shelled brachipods, ostracodes, and gastropods. This unit, which is 2.1 to 4.4 m thick (average of 3.5 m), thins toward the west.

The basal, nodular unit is gradationally overlain by buff coloured, massive to planar laminated and, locally, cross-laminated, quartzose, dolomitic mudstone to wackestone. Small brachiopods, ostracodes and gastropods occur throughout. Pyrite commonly occurs as scattered, 0.5 mm patches of fine crystals. The laminated unit is 1.1 to 3.3 m thick, with an average thickness of 2.2 m. In outcrop at section HR-108 (Fig. 43), the laminated and nodular units have a flaggy weathered appearance (Plate 6B).

The laminated unit grades upward into medium to thickly interbedded, coral-stromatoporoid bindstones and coral-stromatoporoid grainstones and rudstones. The bindstones consist mainly of encrusting stromatoporoids and platy to domal *Alveolites* sp. and *Phillipsastrea* sp. in a fine, buff coloured, mudstone to packstone matrix. Locally the matrix contains abundant abraded fragments of *Thamnopora* sp., *Coenites* sp., crinoid ossicles, brachiopod valves and gastropods. Allochems are commonly partially dolomitized. Locally, some 1 to 3 mm thick, green grey argillaceous partings occur. The grainstones and rudstones consist mainly of abraded fragments of stromatoporoids, *Alveolites* sp., *Thamnopora* sp., crinoid ossicles and some brachiopods. At Twin Falls Creek the bindstone unit occurs at the top of the upper falls (Plate 6B). It is underlain by a discontinuous, recessive shaley unit. The bindstone unit grades upward into finer grained dolomitic limestones containing abundant encrusting, tabular, and dendroid stromatoporoids and some brachiopods, ostracodes and gastropods (Plates 15C, D).

IX. HARDGROUNDS AND HIATUS CONCRETIONS

A. Introduction

The term hardground was introduced by Murray and Renard in 1891 as a descriptive term for rocky sea floors which were found during sampling operations of the Challenger Expedition (Kennedy and Juignet, 1974). Since then numerous studies of these features have resulted in a variety of terminology and classification schemes.

There have been two conflicting explanations proposed for the origin of hardgrounds. Many early workers believed that hardgrounds were the result of emersion and that lithification was the result of subaerial exposure. This theory was strengthened by the view, of some sedimentologists in the 1950's and 1960's, that the process of submarine cementation was insignificant (e.g. Friedman, 1964). Many other workers, however, believed that hardgrounds were produced entirely by submarine processes. Proof of contemporaneous submarine cementation was provided by Milliman (1966) who described extensive lithification of deep water carbonate sediments in the North Atlantic. This process has been confirmed by the widespread discoveries, in both shallow and deep water environments, of penecontemporaneous submarine cementation of modern carbonate sediments (Table 3). In addition, submarine cementation has been widely documented in modern reefs and associated sediments (Table 3).

Over the last decade hardgrounds have received considerable attention because of their value as stratigraphic markers, environmental indicators and their contribution to the understanding of submarine cementation processes. Ancient examples of submarine hardgrounds have been documented from a variety of stratigraphic positions, ages and geographic locations (Table 3).

The Middle and Upper Devonian strata in the area south of Great Slave Lake in the Hay River area are unique in that they contain well preserved surfaces which show signs of

RECENT HARDGROUNDS (author, location)
Milliman (1966)-N. Atlantic; Gervitz and Friedman (1966)-Red Sea; Taft *et al* . (1968)-Bahamas; Bartlett and Greggs (1970)-N. Atlantic; Alexandersson (1969)-Meditteranean; De Groot (1969)- Persian Gulf; Taylor and Illing (1969)-Persian Gulf; Shinn (1969)-Persian Gulf; Wilber and Neumann (1976)-Straits of Florida; Neumann *et al* . (1977)-Straits of Florida; Schlager and James (1978)-Bahamas, deep water; Schlager and Chermak (1979); Bahamas, deep water; Zeff and Perkins (1979)-Bahamas, deep water; Dravis (1979)-Bahamas, shallow water platform; Harris (1979)-Bahamas, shallow water platform; Malfait and Van Andel (1980)-Equatorial Pacific.
SUBMARINE CEMENTATION IN REEFS (author, location-partial listing only)
Macintyre *et al* . (1968)-Barbados; Land and Goreau (1970)-Jamaica; Friedman *et al* . (1974)-Red Sea; James *et al* . (1976)-Belize; Macintyre (1977)-Caribbean; Alexandersson (1978)-Panama; Land and Moore (1980)-Jamaica; Marshall and Davies (1981)-Great Barrier Reef; Macintyre (1984)-Belize.
ANCIENT HARDGROUNDS (AGE, author, location)
PLEISTOCENE; Videtich and Matthews (1980)-Barbados; CRETACEOUS; Voigt (1959, 1973)-N. W. Europe; Bromley (1967, 1975)-N. W. Europe; Scholle and Kennedy (1974)-N. W. Europe; Reitner (1986)-N. Spain; Kennedy and Klinger (1972)-South Africa; Kennedy and Juignet (1974)-France; Jarvis (1980)-France; Jarvis *et al* . (1982)-France; Kennedy and Garrison (1975a)-England; Gale (1980)-England; Jarvis and Woodruff (1981)-England; Glazek *et al* . (1971)-Poland; Moore and Martin (1966)-Texas; Rose (1970)-Texas; Perkins (1971)-Texas; Perkins and Stewart (1971)-Texas; Fürsich *et al* . (1981)-Texas; JURASSIC; Fürsich (1979)-Europe; Palmer and Fürsich (1974)-England; Marshall and Ashton (1980)-England; Purser (1969, 1971, 1978)-France; Fürsich (1973)-France; Fürsich and Palmer (1979)-France; Kazmierczak and Pszczolkowski (1969) -Poland; Gruszczynski (1979)- Poland; Kazmierczak (1974)-Poland; Garrison and Fischer (1969)-Austria; Andersson (1979)-Wyoming, USA; Wilkinson *et al* . (1985)-Wyoming, USA; Jenkyns (1971)-Sicily; TRIASSIC; Zankl (1969)-Austria; MISSISSSIPPIAN; Nichols (1979)-Utah, USA; LATE DEVONIAN; Hecker (1935)-Russia; Koch and Strimple (1968)-Iowa, USA; Stoakes (1980)-Alberta, Canada; Cutler (1983)-Alberta, Canada; Walls and Burrowes (1985)-Alberta, Canada; MIDDLE DEVONIAN; Tucker (1973)-W. Germany; Dunn (1982a, b)-Saskatchewan, Canada; Landing and Brett (1987)-S. W. Ontario, Canada; LATE SILURIAN; Halleck (1973)-Indiana, USA; Mortensen (1985)-Arctic Canada; Jones *et al* . (1979)-Arctic Canada; MIDDLE ORDOVICIAN; Palmer (1978)-Upper Mississippi Valley Region, USA; Palmer and Palmer (1977)-Iowa, USA; Brookfield (1974)-S. Ontario, Canada; Brett and Liddell (1978)-S. Ontario, Canada; Wilkinson *et al* . (1982)-S. Ontario, Canada; Read and Grover (1977)-Virginia, USA; Byers and Stasko (1978)-Wisconsin, USA; EARLY ORDOVICIAN; Lindström (1963)-Sweden; EARLY CAMBIAN; James *et al* . (1977)-Labrador, Canada; PROTEROZOIC; Sarkar *et al* . (1980)-India.

Table 3. Survey of documented hardgrounds and submarine cementation.

early submarine cementation and exposure on the sea floor as rocky surfaces. These surfaces occur at a number of stratigraphic levels throughout the study area. Two main types of discontinuity surfaces can be recognized: (1) hardgrounds, and (2) hiatus concretions. These commonly exhibit features suggestive of early submarine cementation and exposure on the sea floor, including: (1) eroded upper surfaces where both allochems and matrix are truncated, (2) planar to low relief hummocky surfaces, (3) surficial pyritization and rarely glauconitization, (4) encrustation of upper surfaces and in some cases lower surfaces (overhangs) by encrusting epifauna, (5) borings at upper surfaces which have penetrated both allochems and matrix, and (6) presence of bored, pyritized pebbles derived from hardgrounds in adjacent sediment. Many of the hardgrounds have undergone complex periods of sedimentation, bioturbation, omission, lithification, erosion and bioerosion.

The hardgrounds were probably formed in submarine environments. This can be demonstrated by the associated facies and the lack of any features indicative of subaerial exposure and cementation in the vadose zone, such as: (1) keystone vugs, (2) jointing, (3) associated edgewise conglomerate, (4) pendulous or microstalactitic cements, (5) remnants of paleosoil, and (6) solution cavities (Read and Grover, 1977; Donaldson and Ricketts, 1979; Fürsich and Palmer, 1979; James and Choquette, 1983). However, in one case a hardground shows possible solution pitting suggesting that it may have been subaerially exposed for some period of time.

B. Definitions

Following Bromley (1975), the term hardground is herein used for a type of submarine discontinuity surface which was synsedimentarily lithified. Lithified surfaces which indicated nondeposition and breaks in the sedimentary sequence and commonly showed signs of etching and/or organic boring were referred to by early workers as discontinuity surfaces (Bromley,1975). Although Heim (1958) suggested the term subsolution surface for a lithified seafloor which was corroded by subsolution processes, Fürsich (1979) argued that this is simply a special type of hardground. The term hiatus concretion was introduced by Voigt (1968) for early diagenetic concretions that underwent exhumation and colonization on the seafloor before renewed burial. Their genesis and ecology are considered to be similar in many respects to those of hardgrounds (Fürsich, 1979). The term has been applied variously by Hallam (1969), Fürsich (1971), Kazmierczak (1974), Kennedy and Klinger (1972), Kennedy and Garrison (1975a, b) and Baird (1976, 1978, 1981).

Kennedy and Juignet (1974) and Kennedy and Garrison (1975a) suggested that chalk hardgrounds are the end products of a series of depositional and early diagenetic events associated with interruptions in deposition. They recognized a number of distinct stages in the genesis of these hardgrounds: (1) omission surfaces, (2) erosion surfaces, (3) nodular chalks, (4) incipient hardgrounds, (5) simple hardgrounds and (6) composite hardgrounds. Minor erosion surfaces, subsolution surfaces, omission surfaces and hardgrounds were all considered to be types of discontinuity surfaces by Bromley (1975).

Bromley (1975) noted that the trace fossils that are commonly associated with discontinuity surfaces can be subdivided into three categories according to their time relationship with the hiatus. He termed these the pre-omission, omission and post-omission suites. The omission suite was divided into pre-lithification burrows and post-lithification borings.

C. Devonian hardgrounds in the Hay River area

Hardgrounds occur in limestones at or near the top of the Slave Point Formation, at various levels in the Waterways Formation, near the base and top of the Fort Simpson Formation, and at a number of levels in the Escarpment Formation. These occur mainly in fossiliferous mudstones to wackestone and rarely packstones to floatstones. Most of these lithologies consist of microcrystalline calcite with lesser amounts of sparry calcite cement and neomorphic microspar. In some cases the hardgrounds provide useful stratigraphic markers which can be traced over many kilometres.

Based on the surficial morphology, mineralization, and the presence or absence of borings and/or encrusting organisms, the hardgrounds could be subdivided into three main types. These three types of hardgrounds represent end members since they commonly grade laterally or vertically into each other. The classification of the hardgrounds was based upon the examination of 32 thin sections, by petrographic and cathodoluminescence methods and numerous polished hand samples and drill core slabs. The three types of hardgrounds are:

TYPE I-simple hardgrounds; planar to low relief hummocky surfaces, truncation of allochems and matrix at the surface, commonly containing full suite of omission burrows, pyritized surfaces, associated bored and/or unbored hiatus concretions, hardgrounds commonly stacked (Plate 16A-C),

TYPE II-bored hardgrounds; planar to low relief hummocky surfaces, truncation of allochems at surface, full suite of omission traces, pyritization of upper surfaces and, commonly, omission burrow walls, multiple generations of borings which truncate matrix and allochems, associated hiatus concretions (Plates 17, 18A), and

TYPE III-bored and encrusted hardgrounds; planar to hummocky surfaces, commonly with overhangs and cavities, truncation of allochems and matrix at surface, rare surficial pyritization, closely associated bored hiatus concretions, full suite of omission traces, encrustation of upper surfaces and locally undersides of hardground by serpulids, corals and rarely, stromatoporoids (Plates 18B, 19).

D. Type I hardgrounds

Introduction

Rare examples of type I hardgrounds occur in light to medium grey brown, fossiliferous wackestones near the upper boundary of the Slave Point Formation. They occur as single surfaces or in some cases as multiple surfaces below type II hardgrounds. Type I hardgrounds are common in the limestone beds at the top of member A of the Fort Simpson Formation and can be correlated over distances of 15 to 20 km (Figs. 24 to 27). In this case they occur primarily in fine grained argillaceous, light to medium grey, mudstones to wackestones and are represented by single or multiple stacked surfaces. Type I hardgrounds occur locally in members A and B of the Escarpment Formation (Figs. 38, 39) but are not as abundant and are generally laterally discontinuous in comparison to those of member A of the Fort Simpson Formation. However, most of the observations of the hardgrounds from the Escarpment Formation are based on outcrop exposures where these features are commonly masked by weathering and covered intervals. In drill core the hardgrounds are more easily recognizable.

Morphology-lithology

The upper surfaces of type I hardgrounds range from planar (Plate 16C) to low relief hummocky (Plate 16A, B) with a maximum relief of approximately 2 cm. Locally some hardground surfaces exhibit undercut surfaces forming subtle overhangs. The hummocky relief of some hardground surfaces has been accentuated by the erosion of omission burrow fills causing differential downcutting (Plate 16A). In some cases a series of stacked, mineralized hardground surfaces are present (Plate 16B, C). These are commonly separated by only a few millimetres or between 5 to 30 cm.

Microrelief is developed on some of the surfaces and consists of small pits and irregularities on the upper surface of the hardgrounds. In some cases these appear to be small microborings, similar to those which occur at the surface of some type II hardgrounds (Plate 20A). Locally the microrelief resembles a stylolitic contact (Plate 20B). This is especially noticeable where allochems are truncated at the upper surface of the hardground. In this case the allochems have an irregular corroded appearance where they are in contact with the material overlying the hardground. The microrelief on the upper surface may be due to one or a combination of: (1) subsolution or dissolution processes as proposed by Heim (1924, 1958), (2) microbial alteration (boring) similar to that documented from modern hardgrounds by Alexandersson (1972), Zeff and Perkins (1979), Harris (1979) and Dravis (1979) and/or, (3) pressure solution effects concentrated along the upper surfaces of the hardground, similar to those reported from ancient hardgrounds by Wilson (1975), Purser (1978) and Sarkar *et al.* (1980).

The hardgrounds are easily recognizable in core by: (1) the contrast in colouration between the hardground and the overlying lithologies, (2) the dark colour of the upper surface of the hardground due to the presence of disseminated or thin crusts of pyrite, and (3) the mottled appearance of the hardground due to the effects of intense bioturbation and the accentuation of some burrow walls and fills by pyritization.

Type I hardgrounds occur mainly in fine grained wackestones and rarely packstones that consist of abraded crinoid ossicles, and fragments of brachiopod valves, and ostracodes. In most cases the fossil fragments are more or less equigranular. The abrasion and sorting of these particles may have been due to either physical or biological reworking or a combination of the two. Locally, complete brachiopods and ostracodes are abundant. In the Slave Point and Escarpment formations, fragments of bryozoans and *Thamnopora* sp. are common. Blackened, bored and/or unbored pebbles, probably representing hiatus concretions, commonly occur in the fill of omission burrows or in the material overlying the hardgrounds (Plate 16A, C).

The matrix of the hardgrounds most commonly consists of microcrystalline calcite with minor amounts of coarse, blocky to columnar calcite spar and microspar cements, neomorphic calcite, and dolomite. Spar and microspar cements occur in ostracode and brachiopod shells, commonly overlying internal sediments, and between skeletal material (Plate 16B).

Many of the limestone beds at the top of member A of the Fort Simpson Formation have a nodular appearance (Plates 2F, 3B, 4A). These nodules, which are irregularly shaped and have relatively sharp boundaries, appear to be the result of early cementation. In fact, some nodules in the shales are lithified burrow fills, which preserve burrows in full relief.

Many of the nodules show evidence of brittle fracture, with fractures filled by microcrystalline and/or sparry calcite. The fractures are probably the result of expansion due to the force of crystallization of early cements. The nodules probably represent local centres of early diagenetic cementation which led to the formation of nodules in the sediment. The close association of lithified burrow fills indicates that the cementation was probably enhanced through the burrowing activity of organisms. This type of early cementation has been documented in Recent carbonate sediments by Taylor and Illing (1969), Mullins (1983) and Mullins *et al.* (1980) and in ancient rocks by Hallam (1969), Noble and Howells (1974), Goldring and Kazmierczak (1974), Kennedy and Garrison (1975a), Jones *et al.* (1979), Fürsich (1979) and Abed and Schneider (1980).

Sequence of formation -type I- example

Type I hardgrounds represent a complex sequence of early diagenetic, biological, depositional and erosional processes. In the case of multiple generations of stacked hardgrounds these processes have been repeated a number of times. As an example, a type I hardground from near the upper boundary of the Slave Point Formation in HW-79-7 (Plate 16A), probably had the following history of formation: (1) deposition of micritic wackestone, (2) bioturbation of soft or thixotropic sediment producing pre-omission suite of burrows, (3) period of hiatus or omission, with partial lithification of sediment, (4) bioturbation of dewatered and/or partially lithified, firm sediment resulting in emplacement of sharp walled omission burrows, commonly a number of generations of burrows, partial pyritization of burrow walls, (5) renewed sedimentation resulting in fill of omission burrows, pyritization of burrow fill, (6) bioturbation of omission burrow fill by post-omission suite of organisms, (7) complete lithification of hardground and partial lithification of burrow fill, subsequent erosion of upper surface of hardground and partially lithified burrow fill, possible partial glauconitization, (8) renewed sedimentation, fill of topography, and (9) burial of hardground and pyritization of upper surface of hardground.

E. Type II hardgrounds

Introduction

Type II hardgrounds occur at or near the upper surface of the Slave Point Formation and locally near the upper part of member D of the Fort Simpson Formation and member B of the Escarpment Formation. The best examples of this type of hardground occur at the upper boundary of the Slave Point Formation in HW-79-6, HW-80-26 and from a few centimetres below the boundary in JMBS-11.

Morphology-lithology

Type II hardgrounds have planar or low relief hummocky surfaces with a maximum relief of 1.5 cm. Microrelief, similar to that developed on type I hardgrounds, is present locally on some type II surfaces.

The lithology of type II hardgrounds is variable. In samples from HW-79-6 and HW-80-26 the hardgrounds occur in medium to dark brown, bituminous, stromatoporoid floatstone to bindstone (Plates 17, 18A) that are formed mainly of dendroid stromatoporoids, 0.3 to 0.7 cm across, and some large bulbous stromatoporoids. The dendroid stromatoporoids are locally overgrown by encrusting forms. The matrix consists mainly of microcrystalline calcite with between 5 to 15% of abraded crinoid ossicles and fragments of ostracodes and brachiopods. This unit is sharply overlain by light to medium grey mudstone to packstone containing abundant abraded, pyritized fragments of thin shelled brachiopods and ostracodes.

At JMBS-11 the hardground occurs in micritic, fossiliferous wackestone. Abraded fragments of brachiopods, crinoid ossicles and ostracodes form approximately 10 to 15% of the rock. The hardground from the upper part of member B, at section HR-106, consists of fossiliferous packstone that contains abundant fragments of brachiopods, ostracodes, gastropods and crinoid ossicles as well as large fragments of bryozoans and *Thamnopora* sp. Most of this rock consists of microcrystalline calcite with some microspar cement in patches or between skeletal fragments, and neomorphic spar which has replaced some skeletal material.

Many of the skeletal fragments have ragged outlines and corroded interiors that may have resulted from partial micritization.

Borings

The upper surfaces of type II hardgrounds are penetrated by *Trypanites weisei* Mägdefrau (1932). *Trypanites* spp. are a common feature of ancient hardgrounds, and have been documented by numerous workers (Jaannusson, 1961; Lindström, 1963; Koch and Strimple, 1968; Kazmierczak and Pszczólkowski, 1968; Fürsich, 1971; Goldring and Kazmierczak, 1974; Palmer and Palmer, 1977; Palmer, 1978; Brett and Liddell, 1978; Gruszczynski, 1979; Wilkinson *et al.* 1982; Palmer, 1982; Landing and Brett, 1987). Bored hardgrounds have been reported from the Slave Point Formation by Dunham *et al.* (1983), Walls and Burrowes (1985), Tooth and Davies (1987), and from the top of the Swan Hills Formation by Wendte and Stoakes (1987).

Trypanites weisei in type II hardgrounds are parallel to subparallel sided in longitudinal section (Plate 20C), narrow (average 0.9 mm across) and elongate (up to 2 cm long). Boring length is variable (Plate 17). They are commonly perpendicular to subperpendicular to the surface of the hardgrounds. These straight to gently curved, unlined borings are circular to subcircular in transverse section and generally are tapered at their bases (Plate 17). In one sample (HW-79-6) at least two generations of borings are present. In such cases, the fill of one boring is cross cut by a second generation of boring with a slightly different fill (Plate 17, 20D). Similar relationships were documented by Pemberton *et al.* (1987) in borings in stromatoporoid heads from the Late Devonian Waterways Formation of northeastern Alberta. The borings in type II hardgrounds closely resemble the *Trypanites weisei* described by Pemberton *et al.* (1987).

The borings in type II hardgrounds are commonly filled with micrite and fragments of ostracodes, brachiopod valves and crinoid ossicles. The micrite filling the borings is slightly darker than the micrite of the surrounding hardground (Plate 17). This is in part due to the presence of finely disseminated pyrite concentrated along the walls of borings and in the boring fill (Plate 20C, D). Locally some borings are filled by dark brown, microcrystalline peloids that are 0.03 to 0.09 mm long, typically concentrated in the basal parts of the borings. The peloids are cemented (Plate 20E, F) by calcite microspar (0.01 to 0.03 mm across). In some cases the peloids appear to be clumped together in irregular shaped masses (Plate 20F), which have been biogenically reworked. It is tempting to suggest that the peloids in the borings represent the pellets of the organisms which inhabited the borings. However, numerous mechanisms have been suggested to explain peloids, including: (1) the production of pellets by organisms (Macintyre *et al.*, 1968), (2) replacement of aragonite fecal pellets (Shinn, 1969), (3) the fragmentation of calcified algal filaments (Schroeder, 1972), (4) passive fill of interstices by detrital lime silt grains (James *et al.*, 1976), (5) chemical precipitation of calcite by repeated nucleation around centres of growth (Macintyre, 1977, 1984, 1985), (6) spontaneous chemical precipitation of calcite (Marshall, 1983), and, (7) precipitation induced by bacteria (Chafetz, 1986).

The different fills in the borings suggest that there were a number of cycles of erosion and renewed sedimentation after the main phase of erosion which beveled the surface of the hardground. The fill in both generations of borings is different from the material which overlies the hardground. This suggests that the material in the borings was lithified and the surface eroded before the final phase of sedimentation.

Locally the lower parts of some borings are filled by abraded fossil fragments cemented by blocky calcite spar (Plate 17, 21A). This fill is sharply overlain by dark microcrystalline calcite with some fossil fragments. The contact between the two occurs at the same level in each of the borings that contain calcite cements. These borings have penetrated what appears to be a pre-omission burrow (Plate 17). The burrow is recognizable by its roughly circular outline and its relatively dark colouration. The outer margin of the burrow is weakly mineralized by disseminated pyrite which enhances the outline of the burrow. The contact between the spar cement and the overlying micrite occurs at the upper margin of the outer rim of the burrow (Plate 17). Borings in the matrix of the hardground immediately adjacent to the burrow do not contain spar cement (Plate 17). The localized presence of spar cement in these borings suggests that that the burrow may have continued to act as a conduit for calcium rich fluids moving through the hardground, even after lithification of the hardground. The importance of burrows in the initiation and facilitation of early submarine cementation processes has been recognized in both Recent and ancient hardgrounds by Hattin (1968), Shinn (1969), Fürsich (1973), Kazmierczak (1974), Bromley (1975), Kennedy and Garrison (1975a), Palmer and Palmer (1977), Byers and Stasko (1978) and Fürsich (1979). Alternatively, the cementation may have been aided by bacteria associated with the burrow. Carbonate precipitation may be enhanced by sulphate reducing bacteria accompanying the decay of organic material (Brown and Farrow, 1978).

Trypanites weisei which have penetrated the hardground, at the top of member B of the Escarpment Formation, are filled by light brown, idiotopic euhedral dolomite. Some skeletal material is mixed with the dolomite. Dolomite does not cross cut the walls of the borings.

In some cases, small (0.05 mm wide; 0.15 mm long) microborings penetrate the upper surface of the hardgrounds (Plate 20A). The distinction between microborings and macroborings is based on their size, following Golubic *et al.* (1975) who placed the boundary at 100 μm. The isodiametric microborings are slightly curved toward their bases.

Many of the dendroid stromatoporoids (Plate 17) and other skeletal material (Plate 20F), in the sample from HW-79-6, contain borings that resemble *Trypanites* sp. They are commonly preserved as circular cross-sections near the centres of the stromatoporoids. Alternatively, these might represent the axial canals of the the stromatoporoids. However the irregular pattern, pronounced circularity, and constant diameter of the openings and their presence in other skeletal material suggests that they are borings. In this case the borings predate the formation of the hardground. The borings are filled by micrite or microcrystalline peloidal sediment. Locally, this material is overlain by calcite microspar cement (Plate 17). The angles of the geopetals are different in each of the stromatoporoids. This suggests that the stromatoporoids were lying flat on the sea floor at the time of cementation of the geopetal cavities. Reworking of the stromatoporoids resulted in the different orientations of the geopetals. Similar rotated geopetals in *Trypanites weisei* occur in stromatoporoid heads in the Waterways Formation (Pemberton *et al.*, 1987).

Sequence of formation -type II- example

The best example of a type II hardground, which occurs at the upper boundary of the Slave Point Formation in HW-79-6 (Plate 17), clearly shows the complex sequence of events which led to the formation of the hardground. The sequence of events was probably: (1) boring of dendroid stromatoporoids, fill by peloidal sediment and cementation by calcite microspar forming geopetal structures, (2) reworking of allochems and deposition in dark micritic sediment, (3) bioturbation of soft sediment resulting in emplacement of pre-omission burrows, (4) omission during hiatus and early lithification of sediment, (5) repeated periods of bioturbation of firm sediment resulting in emplacement of relatively sharp walled, cross cutting burrow networks, associated pyritization of burrow walls, (6) renewed sedimentation with subsequent fill of omission burrows, pyritization of burrow fill, (7) lithification of hardground and partial lithification of burrow fill, (8) omission during hiatus, erosion resulting in truncation of allochems at surface and differential downcutting into softer burrow fill, (9) emplacement of first generation of *Trypanites weisei*, peloidal fill and pyritization of boring walls and fill, complete fill of borings with microcrystalline sediment, (10) lithification of boring fill and erosion of overlying sediment, (11) emplacement of second generation of *Trypanites weisei* which truncate the first generation borings, partial fill and pyritization, (12) lithification of boring fill, erosion of overlying sediment, truncation of hardground surface, (13) renewed sedimentation, pyritization of upper surfaces of boring fills, bioturbation resulting in emplacement of post-omission burrows in soft sediment overlying hardground.

F. Type III hardgrounds

Introduction

Type III hardgrounds are localized features in the Middle and Late Devonian strata in the Hay River area. They occur at: (1) at the upper boundary of the Slave Point Formation in drill core from HW-79-1, and (2) near the top of member D of the Fort Simpson Formation, 1.1 m above the base of measured section HR-101 (Plates 18B, 19, 21C).

This type of hardground shows the most evidence of sea floor exposure since they are densely bored and encrusted by a variety of epifauna that includes serpulids, corals (Plates 18B, 19B), and stromatoporoids. Locally, in the hardground from member D of the Fort Simpson Formation, the surface of the hardground shows possible evidence of having been subaerially exposed.

Morphology-lithology

The upper surfaces of type III hardgrounds are quite variable. The hardground at the upper boundary of the Slave Point Formation has an undulose surface with a maximum relief of 1 cm. However, the sample is from a 4.5 cm wide drill core, so this figure is somewhat ambiguous. Topographic lows on the surface of the hardground correspond to the eroded fills of omission burrows. This hardground occurs in a *Thamnopora*-stromatoporoid floatstone. The *Thamnopora* sp. and thin, encrusting stromatoporoids which are fragmented and abraded, float in a medium to dark grey brown cryptocrystalline mudstone matrix that contains small fragments of ostracodes and crinoid ossicles. The hardground is sharply overlain by medium grey brown, argillaceous, fossiliferous wackestone of the Waterways Formation.

In contrast the hardground in member D of the Fort Simpson Formation is more topographically and lithologically complex. This hardground outcrops along a cut bank on Hay River, over a distance of about 20 to 30 metres. The hardground occurs in a 50 cm thick quartzose limestone bed which is bounded by recessive silty shales and weathers prominently.

The quartzose limestone bed consists mainly of light brown cryptocrystalline calcite, with 15 to 20% (locally up to 40%) detrital quartz. The distribution of quartz is highly variable. It is generally most abundant in the material overlying the hardground. The quartz grains are subangular to subrounded and 0.02 mm (range from 0.005 to 0.05 mm) long. Locally, the quartzose limestone bed contains small abraded ostracodes, brachiopod valves, crinoid ossicles and rare articulated brachiopods and gastropods. Many of the shell fragments have been partly or totally replaced by calcite microspar.

The upper surface of the hardground is variable being planar to very irregular, with 3 to 4 cm relief. Large (5 to 10 cm long), bored hiatus concretions commonly overlie the material above the hardground and are exposed locally at the surface of the limestone bed (Plates 19A, 22A to D). The hiatus concretions give the surface of the bed a knobbly appearance (Plate 19A). This is due, in part, to the less indurated nature of the material overlying the hardground. The sediment which overlies the hardground appears to have filled in topography on the hardground surface.

Locally, the hardground has a stepped appearance, where the hardground has been eroded and the underlying fossiliferous wackestones have been exposed. Some samples, collected from rubble along the outcrop, are encrusted by serpulids on both upper and lower surfaces. This would suggest that overhangs may have developed in the hardground allowing colonization of undersurfaces. The density of serpulids on the undersides of the hardground, in all cases, was less than that of the upper surfaces.

The upper surface of the hardground commonly has a very irregular surface microtopography due to the density of various borings and possible solution pits. The borings are represented by small circular openings of *Trypanites weisei* and larger (1.0 to 1.3 cm diameter), circular, sharp sided openings (Plate 19A). The large openings, which extend downward up to 0.5 cm into the hardground, commonly taper downward into narrow tubes 0.2 to 0.4 mm wide, with pointed terminations. In some cases these loop and come back to the surface forming U-shaped tubes (Plate 21C). These features appear to be biogenic in origin, however, it is uncertain whether they are borings or burrows since they were not observed to truncate grains or cements. The only clue to suggest that they are borings are the very sharp walls of the openings. The tubes are outlined by dark rims of brown idiotopic, subhedral dolomite and finely disseminated pyrite, which become more diffuse away from the walls of the tubes (Plate 21C). The tubes are filled by light coloured quartzose limestone, which represents a passive fill. These features resemble the prelithification burrows in the Middle Ordovician Bobcageon hardgrounds described by Brett and Liddell (1978; Fig. 3A).

The microtopography on the upper surface is enhanced locally by small irregular pits, 0.02 to 1.0 cm across (Plates, 18B, 19B). These have very irregular, smooth sided outlines and penetrate the hardground to a depth of between 0.1 to 1.0 cm. These features do not appear to be biogenic and may be a solution feature, possibly microkarst. If this is the case, then it is possible that the hardgrounds may have been subaerially exposed for some period of time. The pitted hardground surface is similar to the karren (microkamenitzas) developed at the Silurian-Devonian disconformity in southern Ontario as described by Kobluk *et al.* (1977). They attributed this solution pitting to algal, moss or lichen cover and rainwater or salt-spray dissolution . Most of the evidence points to a submarine origin for the hardgrounds, however, it is possible that the hardground was exposed periodically, and that solution pitting was enhanced by submarine erosion. However, given the nature of the marine shales which bound the hardground, it is difficult to envision how the hardground became exposed.

Another feature which might suggest a period of subaerial exposure during the genesis of the hardground is the relative lack of pyrite at the upper surface. This is a localized phenomenon and occurs only in areas where the upper surface of the hardground is riddled with solution pits. Similar features have been documented by Read and Grover (1977) from Middle Ordovician limestone in Virginia. It is possible, however that this lack of pyrite may be due to removal by currents.

The hardground in member D appears to be laterally discontinuous since it was not detected in any of the adjacent outcrops or drill cores. The thickness of the hardground ranges from 1 to 6 cm.

Encrusting organisms

Type III hardgrounds are encrusted by a variety of organisms. The hardground from the upper part of member D of the Escarpment Formation was encrusted by serpulids and auloporid corals. The hardground from the top of the Slave Point Formation was encrusted by a thin stromatoporoid. Due to the small size of the core, the lateral extent of the encrustation could not be determined.

Serpulids are represented by small, planispiral tubes of *Spirorbis* sp. The spiralled tubes range from 0.05 to 2.0 mm across (Plates 18B, 19B). In some cases the spirals are raised slightly. These tubes closely resemble the attached vermiform gastropods described by Burchette and Riding (1977) from the Carboniferous of England. However, the tubes on these hardgrounds do not have molluscan wall structure, or protoconch and, therefore, are most likely properly assigned to *Spirorbis* sp.

On the hardground surface *Spirorbis* sp. encrust both the matrix of the hardground and skeletal material that is exposed at the surface of the hardground. *Spirorbis* sp. commonly encrust the undersides of the hardground, however, in these cases the number of individuals is reduced in comparison to the upper surface.

In modern carbonate environments, *Spirorbis* spp. are commonly found encrusting *Thalassia* (Nelsen and Ginsburg, 1986). Kazmierczak (1974) noted that serpulid larvae require a clean hard substrate for settlement and are therefore indicative of cemented surfaces. This is supported by the common occurrence of *Spirorbis* sp. encrusting brachiopods and other skeletal material (Plate 21B, D) throughout the Slave Point Formation to the Escarpment Formation of the study area. Similar occurrences have been documented from brachiopods from the Waterways Formation in northeastern Alberta by Norris and Uyeno (1981).

Spirorbis spp. are common in ancient hardgrounds having been documented by Koch and Strimple (1968), Fürsich (1979) and Palmer (1982). Various other species of serpulids have been documented from hardgrounds by Hallam (1969), Purser (1969), Kennedy and Klinger (1972), Voigt (1973), Fürsich and Palmer (1979), Gruszczynski (1979), Marshall and Ashton (1980) and Wilkinson *et al.* (1985).

Encrusting corals occur on the upper surfaces and rarely on the undersides of overhangs in the hardground near the top of member D of the Fort Simpson Formation. The corals, *Aulopora* spp., consist of small (0.8 to 1.0 mm across), "trumpet shaped" corallites arranged in biserial or multiserial rows and/or in web shaped patterns (Plates 19B, 21D). In a manner similar to *Spirorbis* sp., the corals commonly partially or completely encrust brachiopods (Plate 21D). Occurrences of encrusting *Aulopora* spp. on hardgrounds have been documented by Palmer (1982), Koch and Strimple (1968) and Halleck (1973) and hiatus concretions by Goldring and Kazmierczak (1974) and Landing and Brett (1987).

The hardground from the upper boundary of the Slave Point Formation, is encrusted by a 0.8 to 3.0 mm thick stromatoporoid. It overlies truncated stromatoporoid fragments in the matrix of the hardground and *Trypanites weisei* which penetrate both. The encrustation clearly postdates the lithification and omission phases in the development of the hardground.

Sequence of formation - type III - example

The best example of a type III hardground is from the upper part of member D of the Fort Simpson Formation (Plates 18 B, 19, 21C, 22A-D). The generalized sequence of events which led to its formation were: (1) deposition of quartzose carbonate mud, (2) omission during hiatus, and initial early cementation and dewatering of sediment, (3) possible burrowing, causing irrigation of sediments, further selective cementation and development of cavities and overhangs, (4) erosion during hiatus, causing truncation and planing of surface of hardground, collapse of overhangs, to form large pebbles, (5) colonization of upper and exposed lower surfaces of hardground and pebbles by boring and encrusting faunas, (6) possible subaerial exposure causing development of microkarst features, (7) reworking of pebbles, so that all surfaces are bored, multiple generations, and (8) renewal of sedimentation and burial of hardgrounds and hiatus concretions, pyritization of parts of hardground and the walls of borings.

G. Mineralization

In each of the hardgrounds examined the upper surface had been pyritized. Pyritization of hardgrounds has been documented in ancient hardgrounds by Hallam (1969), Halleck (1973), Bromley (1975), Palmer, (1978), Wilkinson *et al.* (1982) and Wilkinson *et al.* (1985). Pyrite commonly occurs: (1) as clumps or irregular masses of crystals along the upper surface or replacing allochems, matrix or cements, (2) as finely disseminated crystals concentrated in a thin (0.1 to 2.0 mm) rim at the upper surface of the hardground and locally along the walls of omission burrows, (3) as thin (0.1 to 1.0 mm thick), continuous crusts which extend along the upper surface, (4) as discontinuous crusts at the surface associated with burrow and boring fills only (Plate 17), and (5) isolated, large (0.1 to 1 cm across), euhedral crystals at the upper surface or in the matrix of the hardground; these commonly have partially replaced skeletal material (Plate 21E). Similar replacement features have been documented in the Middle Ordovician Galena Group (Palmer, 1978).

The most common occurrence of pyrite is finely disseminated crystals concentrated in a 0.1 to 2 mm thick rim at the upper surface of the hardground. In most cases the pyrite becomes more finely crystalline and more diffuse downward, away from the surface of the hardground and away from burrow and boring walls. The fills of some omission burrows and borings commonly contain abundant finely disseminated pyrite.

Rarely, some of the skeletal material at the upper surface had been partially or completely replaced by glauconite. Glauconite is a common occurrence in chalk hardgrounds (Bromley, 1967; Kennedy and Garrison, 1975a; Jarvis, 1980). Jarvis (1980) suggested that glauconitization is a relatively early event and occurs where lithified chalk is in prolonged contact with seawater, but ceases on burial of the hardground.

The presence of pyrite and glauconite in close association with the upper surfaces of the hardground and the walls and fills of omission burrows and borings suggests that organic material may have aided mineralization. Pyrite is intimately associated with both the walls of borings and burrows and their fills. The time relationships of these features to the formation of the hardground suggests that pyritization was an ongoing process throughout the formation of the hardground. The close association of these features and pyritization suggests that organic material was important to the formation of pyrite. Pyritization appears to have taken place at various times throughout the genesis of the hardgrounds, especially from the time of emplacement of omission burrows onward.

The association of biogenic sedimentary structures and mineralization has been alluded to by Ekdale *et al.* (1984) who noted that iron sulphides apparently crystallize in highly localized chemical environments which are poor in oxygen and rich in carbon, iron and reduced sulphur. These conditions commonly exist in association with excrement and decaying corpses that occur in areas of intense bioturbation. As noted by Hallam (1969) and Fürsich (1979), where hardgrounds are pyritized this probably happened after renewed burial since the strongly reducing conditions which are necessary for pyrite formation are incompatible with the high energy environments in which most hardgrounds are formed. With renewed sedimentation and burial of the hardground, conditions within the sediment were probably reducing. These factors coupled with a source of iron and reduced sulphur, probably provided a suitable chemical environment for mineralization.

H. Trace fossil suites

In most of the hardgrounds examined, pre-omission, omission and post-omission burrows are present within or overlying the hardground. As noted by Bromley (1975) the pre-omission suite of trace fossils represents the activities of organisms which churned the sediment prior to the initiation of a hiatus and initial cementation of the sediment. They are generally difficult to recognize because of the lack of contrast between matrix and burrow fill and modification by later cross cutting burrows. However, in some cases active backfill of the burrows is evident by the presence of spreiten. In the hardgrounds examined, pre-omission burrows are commonly represented by vague burrow outlines, which are slightly darker or lighter than the surrounding matrix (Plate 16B, 17). They are commonly horizontal or subvertical and approximately circular to oval in cross section. In some cases the burrows are outlined by concentrations of fine skeletal material around the burrow walls or in burrow fill (Plate 17).

The omission suite of trace fossils is produced during the hiatus under conditions of nondeposition (Bromley, 1975). This suite of burrows is commonly superimposed on the pre-omission suite and can be recognized by their density, contrasted fill and cross cutting relationships. The omission burrows probably remained open at the surface and were passively filled with sediment from above, since they lack any indications of active backfill. In some cases, however, this may have been masked by the activities of the post-omission burrowers which churned the sediment within the omission burrows. In the hardgrounds examined, the omission burrows are recognized by their relatively sharp walls and the different composition and colour of the burrow fills. The burrow walls are commonly accentuated by concentrations of finely disseminated pyrite. These burrows commonly extend several centimetres downward from the upper surface of the hardground (Plate 16A). Locally, some of the burrows are branched indicating that they may represent the traces of *Thalassinoides* (Plate 16A).

Some burrows are filled by light brown, euhedral idiotopic dolomite with some skeletal material. This is a common occurrence in the hardgrounds in the Waterways, Fort Simpson and Escarpment formations. Dolomite preferentially associated with burrow and/or boring fills has been documented by Shroud and Levin (1976), Morrow (1978); Byers and Stasko (1978); Brown and Farrow (1978); Jones *et al.* (1979); Delgado (1980); McHargue and

Price (1981), Narbonne (1984); Pickerill *et al.* (1984a), Sheehan and Scheifelbein (1984), and Pemberton *et al.* (1987). Locally, more than one generation of omission burrows are present. This is evident from the cross cutting nature and contrasted fill of some burrows. Commonly the omission suite of trace fossils has been truncated at the upper surface of the hardground. Differential erosion has resulted in an increased downcutting into omission burrow fills which probably were not completely lithified at the time of erosion (Plate 16A). The resultant depressions left at this surface are commonly filled by sediment which was lithified and surficially pyritized before another period of erosion removed the overlying sediment (Plate 16A).

Post-omission burrows occur in the sediment that buried the omission surface (Bromley, 1975). These burrows commonly modified the the fills of omission burrows. In the hardgrounds examined, post-omission burrows are represented by vague horizontal or subvertical burrow outlines in the sediment overlying the hardground or within the fill of omission burrows. Locally, the surface of the hardground appears to have imposed a horizontality (*sensu* Bromley, 1975) on the burrows in the overlying sediment since they are commonly deflected along this surface but do not penetrate it (Plate 18A). They are defined by their contrasted colours and burrow fills in comparison to that of the omission burrows. Post-omission burrows in the material above the hardground are commonly filled by euhedral idiotopic dolomite. Post-omission burrows within the fill of omission burrows do not cross cut the walls of omission burrows.

I. Evidence of early lithification and sea floor exposure

A number of features indicate that the hardgrounds were synsedimentarily lithified exposed at the sea floor. In each of the samples examined, skeletal material had been sharply truncated at the upper surface of the hardground (Plates 17, 18, 19A, 21E). This suggests that the skeletal material was firmly cemented in the matrix of the hardground and that the matrix was at least as hard as the allochems prior to the onset of scour and erosion at the seafloor.

Truncation of allochems was most noticeable in type II and III hardgrounds.

The second line of evidence is the planar to hummocky relief on the upper surface of the hardgrounds and the sharp lithologic break at this upper surface. This sharp break was most pronounced in the hardgrounds developed at the top of the Slave Point Formation. Locally, overhangs are developed at the surfaces of some hardgrounds, especially the type III hardgrounds from near the top of member D of the Fort Simpson Formation. In this case, large areas of the undersides of the hardgrounds were exposed as demonstrated by the encrustation of the undersides by serpulids. These features suggest that the matrix of the hardground was lithified before erosion took place.

Possible evidence for early lithification is provided by the presence of omission burrows in the hardgrounds. These are commonly relatively sharp walled, with no signs of compaction, and in places branch and cross cut pre-omission burrows and other omission burrows. The superposition of the omission suite of traces suggests that the hardground initially passed through a soupground and firm ground stage. As noted by Ekdale *et al.* (1984) sediment compaction and dewatering can transform a deposit from a soupground to a firmground. However, in these cases it is possible that compaction and dewatering occurred simultaneous with the onset of early submarine cementation. The hardgrounds were probably completely lithified during the emplacement of the post-omission burrows in the overlying sediments since the post-omission burrows, in the sediment immediately overlying the hardground (Plate 18A), commonly have an imposed horizontality.

In some cases the upper surface of hardgrounds were penetrated by small cracks from 0.025 to 0.75 mm across. These are widest at the top and taper downward from the hardground surface to hairline fractures (Plate 17). The cracks are very localized features and only extend downward from the surface for about 0.5 to 1.0 cm. The fractures are healed by blocky calcite spar. They penetrate matrix only and are deflected around small allochems.

In a type II hardground from the top of the Slave Point Formation the cracks penetrate some of the larger allochems, namely the dendroid stromatoporoids. The fractures post date lithification of the hardground but predate some of the borings in the hardground. Some borings and boring fills are cross cut by fractures whereas some borings cross cut fractures (Plate 17). These features are suggestive of a lithified sediment. Similar cracks in hardgrounds were documented from Middle Ordovician hardgrounds by Palmer and Palmer (1977), Brett and Liddell (1978) and Delgado, (1980), and Late Devonian hardgrounds by Stoakes (1980).

Shinn (1969) and Fürsich and Palmer (1979) described submarine polygons and pseudoanticlines from recent and ancient hardgrounds, respectively. They suggested that these features were probably formed by sediment expansion due to the force of crystallization of early submarine cements. The fractures in the hardgrounds in this study were probably not formed in this manner because the fractures cross cut some boring fills which were obviously emplaced after complete lithification of the hardground. Palmer and Palmer (1977) and Brett and Liddell (1978) noted that fractures in Middle Ordovician hardgrounds cross cut borings or allochems and thus postdate the early stages of sediment lithification.

The stylolitic upper surfaces which occur locally in some hardgrounds are suggestive of a lithified substrate. This type of feature has been noted in ancient hardgrounds by Wilson (1975), Kennedy and Garrison (1975a), Kennedy and Garrison (1977), Purser (1978) and Sarkar *et al.* (1980). As noted by Wanless (1979) sutured stylolites occur only in, or at the boundaries of limestone units which have a structural resistance to stress, in this case early cementation of the hardground.

Many of the hardgrounds contain, at the upper surface and/or within omission burrow fills, black or dark rimmed hiatus concretions. In some cases, the concretions contain a high density of *Trypanites weisei* and are encrusted by serpulids, auloporid corals and rare favositid corals. In many cases, hiatus concretions occur in limestone beds or shales, which are located stratigraphically above or adjacent to beds containing hardgrounds. These features strongly suggest that the concretions may be the reworked remnants of eroded submarine hardgrounds.

The most conclusive evidence for lithification and exposure to the sea floor as a rocky bottom is found in type II and type III hardgrounds where the upper surfaces are (1) penetrated by *Trypanites weisei* and (2) penetrated by *Trypanites* and unidentified borings or burrows and encrusted by epifauna including corals, serpulids and rare stromatoporoids, respectively. Borings penetrate both allochems and micrite matrix. These features indicate that the sediment was firmly lithified prior to the colonization of the upper surface.

The lack of boring infauna and encrusting epifauna at the upper surface of type I hardgrounds suggests that conditions were inhospitable for colonization. This may have been the result of a hiatus of short duration followed immediately by renewed sedimentation or possibly to intense scour and erosion during the hiatus producing conditions which were not conducive to the settling of larvae.

J. Cementation of hardgrounds

The matrix of the hardgrounds consists primarily of ferroan microcrystalline calcite with some patches of spar and microspar, and contains a variable amount of skeletal material and other allochems and rare detrital quartz. In some cases skeletal material has been replaced partially or completely by calcite microspar

The very fine crystalline nature of the matrix creates problems when trying to determine what the early cements responsible for the formation of the hardground were. For example, was the microcrystalline calcite deposited as a sediment or was it precipitated as cement in pore space. This problem has perplexed many workers. As noted by Harris *et al.* (1985) the seemingly simple relationship between mud percentage and bottom agitation (as alluded to by Folk, 1962 and Dunham, 1962) is complicated since mud size carbonates in reef rock and hardgrounds may actually be microcrystalline cement and not related at all to low energy settling.

Sparry calcite cements are rare in the hardgrounds. In these cases the spar commonly occurs in geopetally filled cavities in brachiopods and other skeletons, between skeletal particles, and rarely in pore spaces in the matrix of the hardground.

In an attempt to differentiate cements from sediment, thin sections were examined with cathodoluminescence. This proved useful for determining early versus late cements, but was of little value for the microcrystalline calcite. In each of the thin sections examined, the fine microcrystalline calcite matrix of the hardgrounds had a moderate to bright orange luminescence (Plate 23). The intensity of the luminescence was more or less the same from hardground to hardground. Locally, the matrix had a dull blue-purple tint near the upper surface of some hardgrounds which graded downward into bright orange luminescence. The blue luminescence only occurs where there is finely disseminated pyrite concentrated along the surface. It would seem logical to suggest that a portion of the microcrystalline matrix of the hardgrounds must have been precipitated as early cement since sparry calcite cements account for such a small proportion of the hardground. In order for the hardground to have been lithified most of the cement must have been microcrystalline.

In type II hardgrounds from the top of the Slave Point Formation, the microcrystalline fill of *Trypanites weisei* was bright orange to orange yellow luminescent (Plate 23A, B). The luminescent boring fills were brighter than the surrounding microcrystalline matrix of the hardground(Plate 23A, B). First and second generations of borings showed no difference in the luminescence of their fills.

Calcite cements lining the interior of brachiopod shells exhibit a more complex history of cementation. One of the best examples is from a type I hardground in HW-79-3, from near the top of member A of the Fort Simpson Formation (Plate 23C, D). The earliest cements consist of dull orange luminescent microcrystalline calcite. This is overlain by small (0.02 to 0.05 mm wide, 0.1 to 0.5 mm long), columnar crystals of non-ferroan calcite that line the interior of the brachiopod shell and overlie internal microcrystalline sediment at the base of the shell (Plate 23C, D). The columnar crystals have a bright orange luminescence, with a pronounced bright and dull zonation. These are followed by a third generation of cement consisting of larger (0.5 to 0.75 mm wide, 1.25 to 2.0 mm long), blocky, ferroan calcite spar crystals, which are moderate to dull orange luminescent (Plate 23C, D) and exhibit a faint zonation. A fourth generation of cement consists of even larger crystals (0.75 to 1.0 mm wide, 1.5 to 2.25 mm long) of blocky, ferroan calcite, which have a sweeping, brush-like extinction pattern in cross polarized light and are non-luminescent (Plate 23C, D).

The earliest generations of cements occur mainly in large cavities such as brachiopod shells. Elsewhere, they occur in intraskeletal porosity, in pore spaces in the matrix and interparticle porosity. In the spar filled borings which had penetrated an pre-omission burrow, from the type II hardground at the top of the Slave Point Formation (Plate 21A), the spar exhibited a first generation of dull orange luminsecent calcite and a second generation of calcite with a pronounced bright and dull orange luminescent zonation (Plate 23A). These were sharply overlain by bright orange luminescent microcrystalline calcite (Plate 23A). Fractures which penetrated the surface of hardgrounds contained non-luminescent or dull red luminescent calcite (Plate 23B).

The exact time relationships between the emplacement of the earliest microcrystalline cements and the pore lining, non-ferroan, luminescent cements could not be determined. It appears, however, that the precipitation of the first generation of pore lining microcrystalline cements may have been a pervasive phenomenon based on the homogeneous luminescent nature of the calcite in the matrix of the hardgrounds. The second generation of zoned, dull and bright orange luminscent, ferroan calcite appears to be more localized in its distribution. These cements fill intra- and interskeletal porosity and in some cases, the lower parts of borings which have penetrated pre-omission burrows. This lends support to the argument that burrows may have acted as conduits for early cements. The latest stage cement is the non-luminescent, ferroan spar which occurs at the centre of cavities and in fractures which penetrate the surface of the hardgrounds.

Cathodoluminescence has been used sparingly as a technique for studying hardground cements. Wilkinson *et al.* (1982) and Wilkinson *et al.* (1985) used cathodoluminscence to examine the cements in Middle Ordovician and Jurassic hardgrounds, respectively. In both cases, they determined that early cements were luminescent. In the case of Jurassic hardgrounds, the luminescent cements ranged from dull orange to bright yellowish orange. None of the early cements exhibited luminescent zoning. In the Middle Ordovician hardgrounds the early cements luminesced a bright orange while the late cements were non-luminescent. This is similar to the observations of the hardgrounds examined in this study.

K. Distribution of hardgrounds

Introduction

The hardgrounds occurring at or near the upper boundary of the Slave Point Formation and near the top of member A of the Fort Simpson Formation are relatively widespread. In comparison, those in the Waterways Formation, the upper part of member D of the Fort Simpson Formation and the Escarpment Formation are localized features of discontinuous lateral extent.

Slave Point Formation

Of the 18 cores examined from the top of the Slave Point Formation, only six contained hardgrounds (Fig. 44). The distribution of these features appears to be intimately related to the presence of topographic highs which correspond to thick sections of the Slave Point Formation on the isopach map (Fig. 44). The hardgrounds are mainly of type II with only one occurrence each of type I and III.

The hardgrounds are developed at the top or within regressive, shallow water, platformal carbonates. The close association of the hardgrounds with topographic highs suggests that conditions were more favourable for early cementation in these areas, than in the

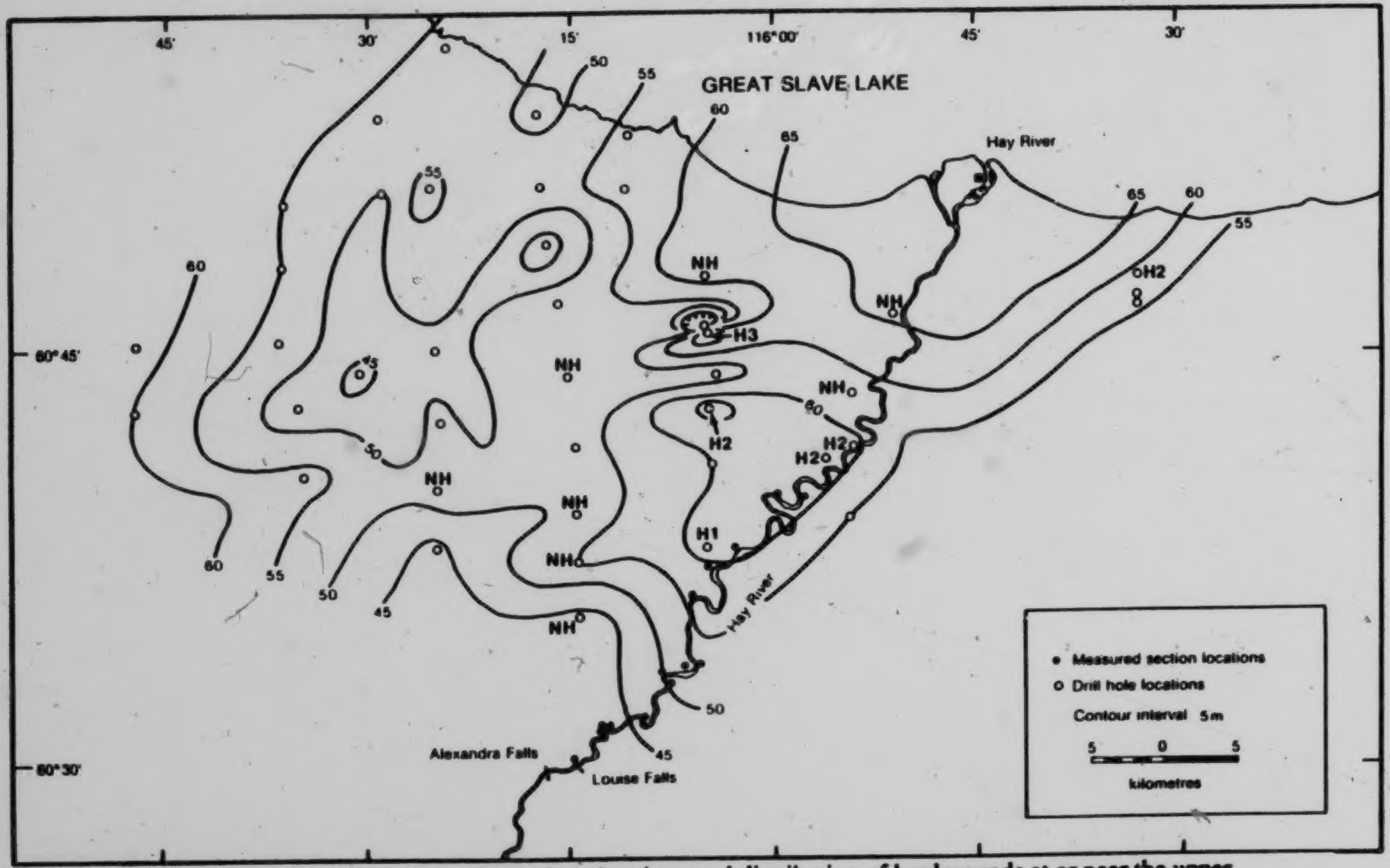


Figure 44. Isopach map of the Slave Point Formation showing areal distribution of hardgrounds at or near the upper boundary of the formation. Hardgrounds are designated as type I (H1), type II (H2) type III (H3) and no hardground (NH).

surrounding, low lying areas which are devoid of hardgrounds. The close association between shallow water hardgrounds and areas of elevated bottom topography has been documented by Shinn (1969), Fürsich (1979) and Dravis (1979).

Hardgrounds at the top of the Slave Point Formation are commonly overlain by 1 to 3 cm of argillaceous packstone, grading up into more open marine, interbedded calcareous shale and argillaceous limestone, of the Waterways Formation. These sediments were probably deposited during a transgression. The hiatus responsible for the initiation of the hardground may have been the result of a rapid transgressive event. As noted by Kendall and Schlager (1981), widespread hardgrounds probably trace sea level rises during which carbonate sedimentation ceases and cementation, boring and grazing result.

Hardgrounds are a common feature of the Dawson Bay Formation, which is slightly older than the Slave Point Formation, in Saskatchewan (Dunn, 1982a, 1982b). Braun and Mathison (1982, 1986) related the development of hardgrounds in the Dawson Bay Formation to upward movements of the Peace River Arch in Alberta. They suggested that this movement had a "destabilizing influence" and caused "unrest" in the basin. They have not made it clear, however, how this movement could have initiated a hiatus that was responsible for hardground formation. Is it possible that upward movement of the Peace River and/or Tathlina Arch could have caused a relative rise in sea level which might have choked sedimentation in littoral areas, thus promoting a hiatus?

Waterways Formation

Of the 17 drill cores which penetrated the Waterways Formation, only 4 contained hardgrounds (Fig. 45). The hardgrounds are patchily distributed and are generally laterally discontinuous. Due to the relative homogeneity of the limestones and lack of marker beds in the formation, it was difficult to assess the correlatability of the hardgrounds. The hardgrounds in the Waterways Formation are all of type I. The patchy distribution and incomplete development (*i.e.* type I) of the hardgrounds might indicate that conditions were

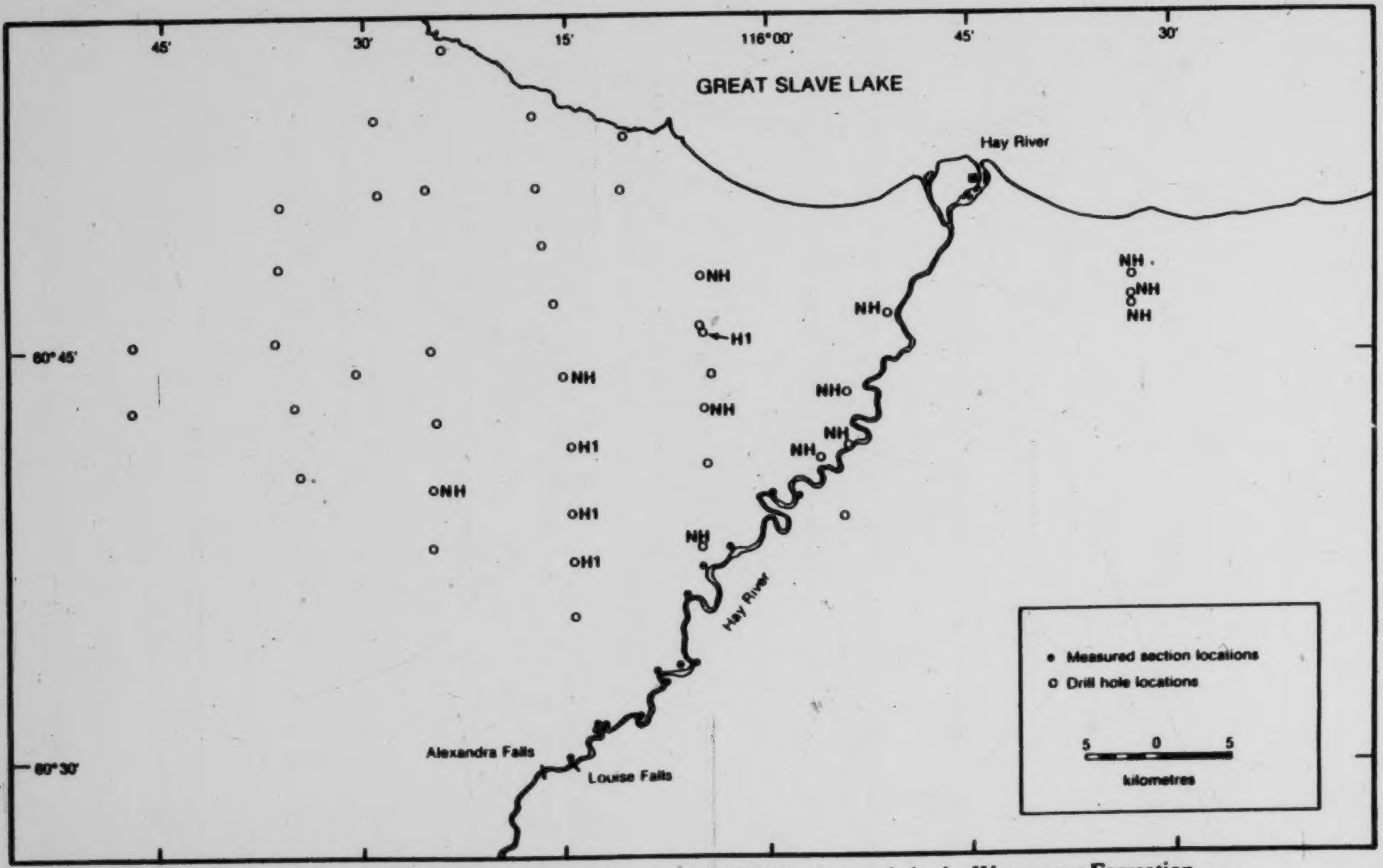


Figure 45. Drill hole location map showing areal distribution of type I (H1) hardgrounds in the Waterways Formation. (NH represents cores which did not contain hardgrounds).

relatively unfavourable for the development of these features. There was probably a relatively high, constant rate of sedimentation and lack of bottom currents associated with the deposition of the shales and carbonates of the Waterways Formation.

Fort Simpson Formation

The most widespread and widely correlatable hardgrounds occur at the top of member A of the Fort Simpson Formation. The type I hardgrounds in the uppermost limestone bed of the member can be correlated over an area of about 400 km^2. The hardground occurs at roughly the same stratigraphic interval in each of the cores examined.

Of the 13 drill cores which penetrated the member, 12 contained type I hardgrounds (Fig. 46). No hardgrounds were found in the core from the most basinward drill hole (HW-79-10). The hardgrounds occur in two positions in member A: (1) near the top of the uppermost limestone bed in the member, and (2) in limestone beds several metres below the upper boundary of the member. The stratigraphically lower hardgrounds are laterally discontinuous. The limestone bed and associated hardgrounds at the top of the member forms a distinctive marker throughout the Hay River area. This marker is readily detectable on geophysical logs and has a very gently sloping profile (less than 1°). Similar sloping markers (with slightly greater values of slope) have been documented in the basin-filling shales of the Ireton Formation (McCrossan, 1961; Oliver and Cowper, 1963; Sheasby, 1971; Stoakes, 1980), the Hay River Formation (Williams, 1977) and the Besa River Formation (Pelzer, 1966). These features were interpreted as clinoforms following the work of Rich (1951).

Log markers in the Ireton Formation were found by Stoakes (1980) to be characterized along certain portions, by submarine hardgrounds. He noted that the hardgrounds were most "completely developed" on the platform portions of the marker profile, and less so on the upper foreslope and basinal portions. Hardgrounds were absent from most of the middle of the sloping part of the marker, being developed only where calciturbidites formed the substrate. Stoakes (1980) suggested that the lack of hardgrounds on some parts of

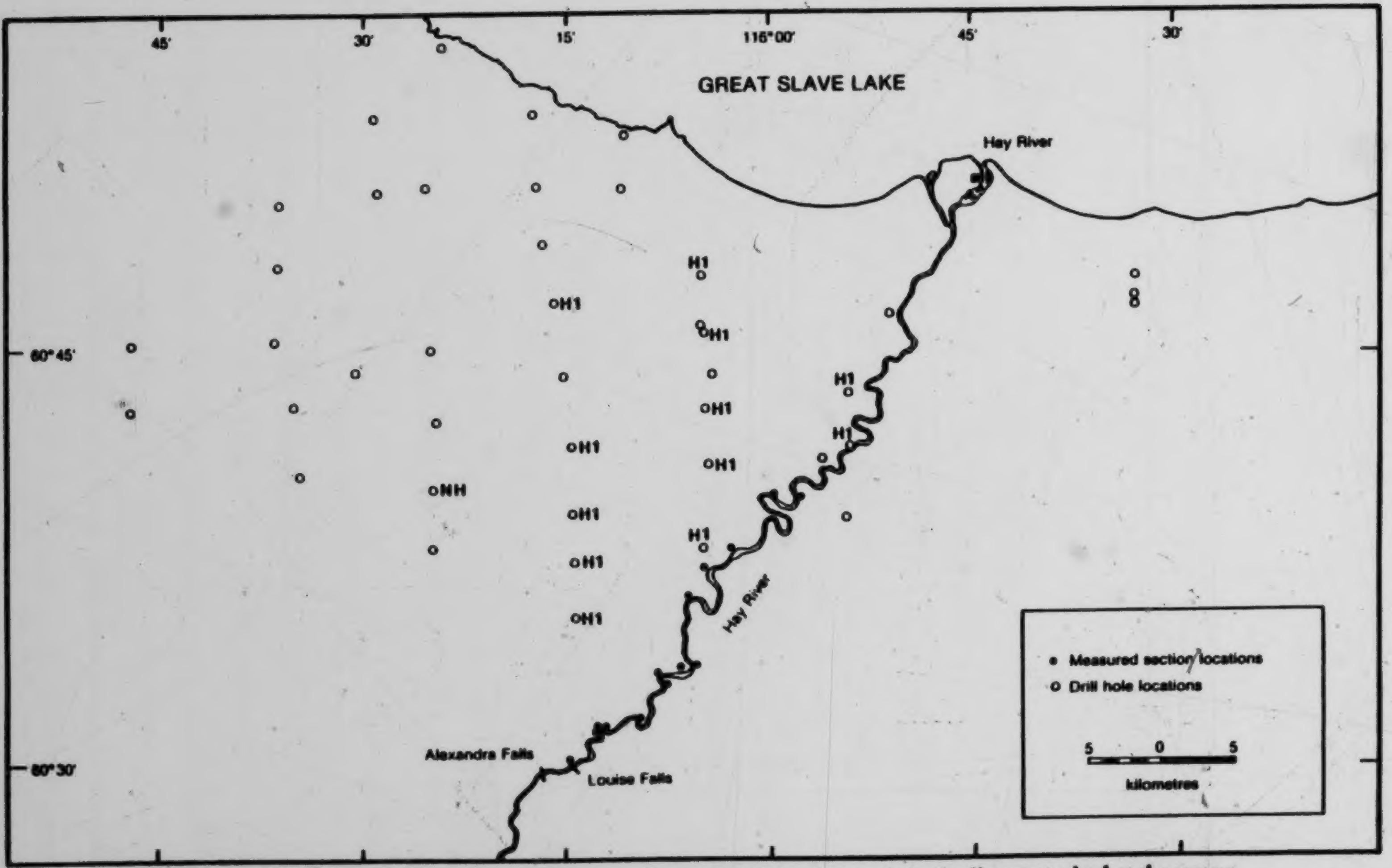


Figure 46. Drill core location map showing areal distribution of type I (H1) hardgrounds in the limestone bed at the upper boundary of member A of the Fort Simpson Formation. (NH represents cores which did not contain hardgrounds).

the markers was due to a high argillaceous content of the slope sediments. In comparison, Cutler (1983) noted that hardgrounds in the Grosmont Formation occur only in argillaceous lithologies in slope positions and are absent from clean platformal lithologies. It should be kept in mind that, due to the lack of complete cores, examination of any one marker bed over its entire geographic extent was impossible. Therefore, in order to characterize the lithologic composition of the beds, Stoakes (1980) assembled samples from a number of different markers into one idealized marker. Thus many of his observations on the distribution of the hardgrounds are subject to some uncertainty.

The hardgrounds at the top of member A of the Fort Simpson Formation were probably formed in relatively deeper water than those of the Waterways Formation and undoubtably the Slave Point Formation. The hardgrounds are, in every case, overlain by limestones of similar lithologic composition to that of the hardground indicating that pre- and post-omission sedimentation took place under similar conditions. This fact, plus the lack of borings and encrusting epifauna, suggest that the hiatus responsible for the hardground was of relatively short duration. Multiple generations of stacked hardgrounds are common, which might indicate a cyclicity or some sort of pulsing of the phenomenon responsible for the hiatus, possibly a pulsing of relative sea level rise. The widespread nature of the hardground at the top of member A is indicative of a widespread hiatus event. In a manner similar to that of the Waterways Formation it is possible that a relative rise in sea level was responsible for the initiation of a hiatus leading to the formation of the hardground. A similar mode of genesis of the hardgrounds from the Ireton Formation was postulated by Stoakes (1980).

The initiation of cementation of the hardgrounds at the top of member A may have been due to a number of factors, such as bottom contour following currents and bioturbation similar to that suggested by Mullins *et al.* (1980) from deep water Bahamian slopes. They noted that cementation in this area is controlled by a combination of physical, biological and chemical processes. Bottom currents enhance synsedimentary cementation by: (1) increasing the permeability of the sediment by winnowing muds, (2) creating pauses in sedimentation which allows the sediment to be exposed at the sediment water interface, and (3) providing large volumes of seawater containing the necessary cations for cementation (Mullins *et al.*, 1980). Burrowing organisms tend to irrigate the shallow subsurface sediments which may increase the interstitial circulation and enhance cementation (Mullins *et al.*, 1980).

The incomplete development of the hardgrounds, in addition to representing a short period of hiatus, might also be due in part to deposition in a pelagic environment, where abundant clay material was being deposited. The detrimental effect of clays and argillaceous material on the formation of hardgrounds has been alluded to by Zankl (1969) and Goldring and Kazmierczak (1974). Where clay material or insoluble residue exceeds 2%, early crystallization of cements is inhibited (Zankl, 1969).

The type III hardground from near the top of member D of the Fort Simpson Formation is of very limited lateral extent. However, it is one of the most completely developed hardgrounds in the study area, and appears to represent a relatively lengthy hiatus, or alternatively deposition under high energy conditions, during which the hardground was bored and encrusted. The latter appears to be more feasible as shown by the occurrence in the surrounding strata of tempestites, current bedded, calcareous siltstones and firmgrounds. Additional evidence for this is provided by the large, bored and encrusted hiatus concretions which probably represent eroded and reworked hardgrounds from the adjacent sediment.

Escarpment Formation

Hardgrounds of type I and II are very localized features in the limestones of the Escarpment Formation.

L. Hiatus concretions

Introduction

Hiatus concretions occur throughout the strata in the study area. They were found in limestones of the Slave Point Formation and in limestones and less commonly, shales of the

Waterways, Fort Simpson and Escarpment formations where they commonly occur in close association with hardgrounds. In some cases the concretions probably represent reworked hardgrounds whereas others are probably the result of selective centres of early diagenetic cementation. In both cases the term hiatus concretion is used to describe these features, although this may differ somewhat from the usage of Voigt (1968) and Kennedy and Klinger (1974).

Morphology-composition

The hiatus concretions are variable in both morphology and composition (Plate 22). They are generally larger than 0.5 cm. The largest concretions occur in the hardground in member D of the Fort Simpson Formation, which had maximum dimensions of 12 cm long x 10 cm wide x 4 cm thick. The average size of the concretions was about 3 x 3 x 2 cm. They are always smooth, irregularly shaped and commonly have narrow (0.5 to 1.0 cm), shallow (0.02 to 0.05 cm), linear depressions which transect the outer margins (Plate 19A). These surficial depressions appear to biogenic in origin and may represent burrows. The concretions are as indurated as the hardgrounds with which they are associated, since they commonly weather out in relief (Plates 19A, 22 B to D).

The irregular nature of the surface of the concretions is enhanced by the presence of *Trypanites weisei* that occur on all sides of the concretions giving the surface a fine pitted appearance (Plates 19A, 22 A to C, E). In many cases the concretions show evidence of abrasion since some of the borings have been truncated. Additional evidence of abrasion and reworking is the presence of highly abraded brachiopod valves and crinoid ossicles in the sediment surrounding the concretions. The borings are commonly filled with light coloured micrite. Many of the concretions, especially the smaller ones, are not bored. Locally, in the examples from member D of the Fort Simpson Formation, the hiatus concretions are encrusted by corals (Plate 22A) and serpulids.

Lithologically, the concretions consist primarily of mudstones to wackestones.

However, locally they range from grainstones to quartzose limestones. These compositional types only occur in member D of the Fort Simpson Formation and in the Escarpment Formation. In general, where the concretions overlie, are contained within, or occur in stratigraphic proximity to a hardground, they usually have the same composition as that hardground.

The most striking feature of the concretions and one that makes them easily recognizable in the field and in drill core, is their dark colouration. They are almost always, black to dark grey or have a black or dark grey rim (Plates 22A, B, E). This dark colouration is due to the presence of very finely disseminated pyrite, which in the case of black concretions is dispersed throughout. In some cases a number of generations of rimming pyrite are evident (Plate 22E). The dark colouration of the concretions is in stark contrast to the light coloured microcrystalline calcite in the borings.

Borings

The borings in the hiatus concretions are similar to those seen in type II hardgrounds and can be assigned to *Trypanites weisei*. They commonly occur in very dense concentrations in the concretions. In some cases a number of generations of borings are present as evidenced by the cross cutting relations of some borings (Plates 22A, B, E). The greatest density of borings usually occurs on the surface of the concretion which is oriented upward, with relatively lower density on the surface which is buried (Plate 22A, B). Similar distributions of borings were reported by Hagdorn (1982) on "*Placunopsis*-biostromes". He noted that the densest boring and encrustation occurred above the level of the surrounding sediment on exposed surfaces. Less dense boring and encrustation, on the flanks of the biostromes, occurred during storm generated lower sediment levels (Hagdorn, 1982).

The borings almost always have pyrite "halos" (Plate 22A, B, E). The sediment in the concretion, surrounding the boring wall contains finely disseminated pyrite which is concentrated in a thin (0.2 to 1 mm) rim.

The distribution of the borings on all sides indicates that the concretions were reworked and periodically overturned. This overturning would allow colonization of the concretions, on all sides by boring infauna.

Encrustation

Encrusted hardgrounds occur in association with the hardground in member D of the Fort Simpson Formation. The most common encrusters are *Spirorbis* sp. and *Aulopora* sp. These occur mainly on the upper surfaces of the concretions, however, they also occur on lower surfaces. In one example a hiatus concretion was encrusted by a small *Alveolites* sp. (Plate 22A). The encrustation of the concretions appears to post date the boring phase since borings are commonly covered by encrusters and encrusters are never bored.

Genesis

A number of origins have been proposed for hiatus concretions, all of which involve some form of early diagenetic cementation below the sediment-water interface, commonly but not always, in association with hardground formation. The following are the most widely cited origins of hiatus concretions: (1) localized centres of early cementation forming nodules or incipient hardgrounds, winnowing and exposure of nodules, colonization by encrusting and/or boring organisms, burial (Kennedy and Klinger, 1974; Baird, 1976, 1981; Fürsich, 1979), (2) fill and cementation of fine material in shells, dissolution of shell material, exposure, mineralization, encrustation and/or boring, burial (Kennedy and Garrison, 1975b), and (3) early cementation around burrows, reworking of concretions, colonization by encrusting and/or boring organisms, burial (Kazmierczak, 1974). The latter process has been documented from recent sediments on the west coast of Scotland by Brown and Farrow (1978). Bored black limestone pebbles have been reported from Cambrian platform margin carbonates from Virginia by Pfeil and Read (1980) and from shelf carbonates from the Cenozoic of New Zealand by Nelson (1978).

Similar features may develop by other processes and may be difficult to distinguish from true hiatus concretions. Fürsich (1979) noted that shallow marine hardgrounds that have been subjected to a particularly strong period of erosion may be reworked. This would result in the hardground being broken up and reworked into pebbles, which would commonly come to rest on laterally equivalent hardgrounds (Fig. 47). Erosion of the hardground is probably facilitated by open burrow systems with cavities and overhangs (Fig. 47) developed (Fürsich, 1979).

Hiatus concretions and reworked hardgrounds, especially if they are not bored or encrusted, may be difficult to distinguish from other types of black limestone pebbles. A number of workers have documented the occurrence of conspicuously black, centimetre sized calcareous pebbles, in recent carbonate sediments and ancient rocks (Maiklem, 1967; Folk and Wilson, 1970; Barthel, 1974; Strasser and Davaud, 1983; Strasser, 1984). The dark colouration of the clasts are thought, in most cases, to have originated by impregnation by organic material, sometimes with the addition of pyrite, in low Eh/high pH environments (Strasser and Davaud, 1983). This type of black pebble is generally regarded as being a product of early diagenetic cementation in shallow water coastal environments or terrestrial environments (Barthel, 1974; Strasser and Davaud, 1983).

It would appear that the hiatus concretions associated with the type III hardground in member D of the Fort Simpson Formation may represent reworked hardgrounds. This is suggested by: (1) the relatively large size of the concretions, (2) the similar lithology of the concretions and the hardground, (3) similar encrusting and boring histories, (4) the presence of overhangs and cavities in the underlying hardground, which may have facilitated its erosion, and (5) the abundance of highly abraded skeletal material in close association with the concretions. However, it is possible that they may have formed in a slightly different manner. They may represent the remains of an exhumed and reworked, discontinuous or incipient hardground which formed in the sediment laterally adjacent to the type III hardground (Fig. 47).

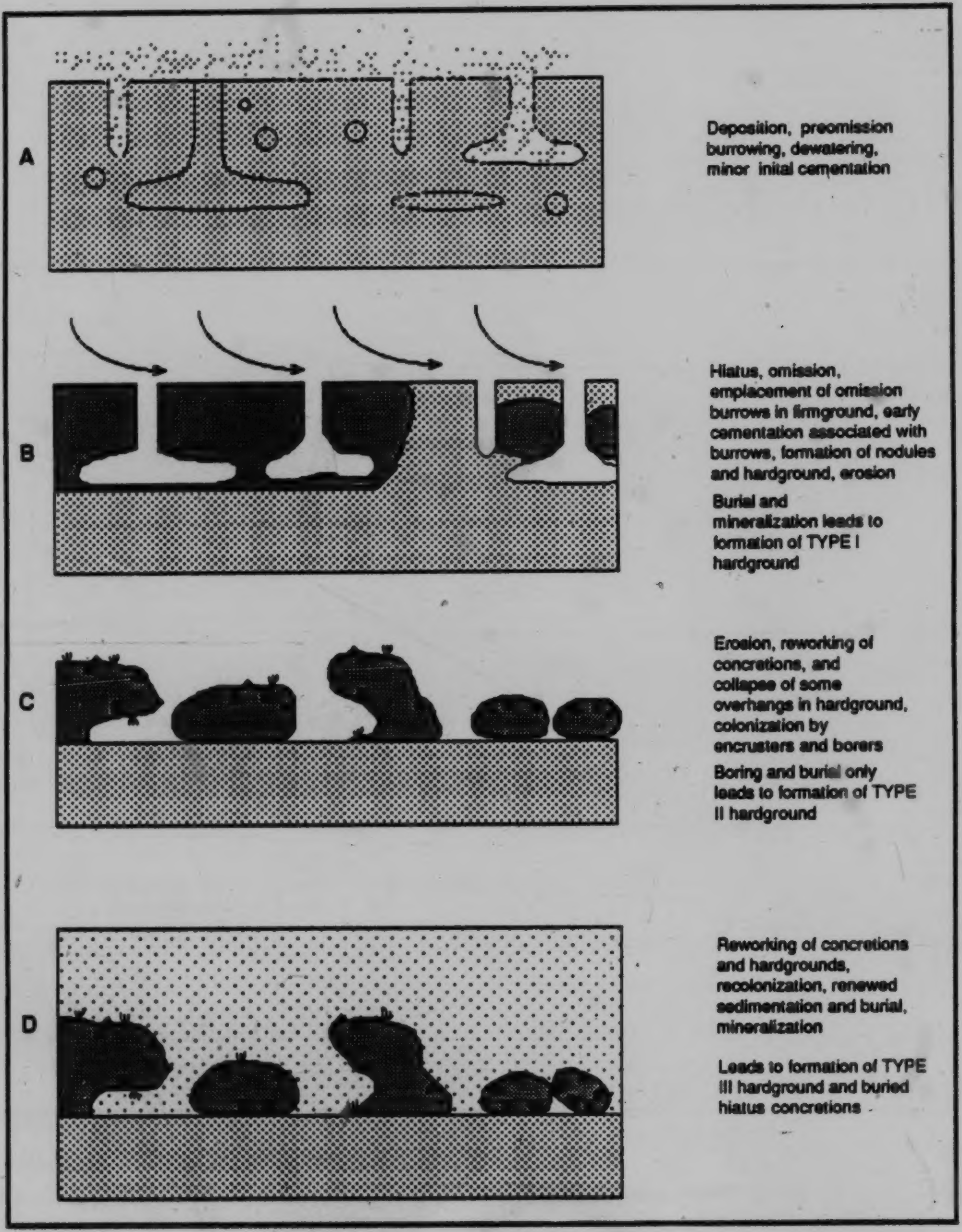

A
Deposition, preomission burrowing, dewatering, minor inital cementation
B
Hiatus, omission, emplacement of omission burrows in firmground, early cementation associated with burrows, formation of nodules and hardground, erosion
Burial and mineralization leads to formation of TYPE I hardground
C
Erosion, reworking of concretions, and collapse of some overhangs in hardground, colonization by encrusters and borers
Boring and burial only leads to formation of TYPE II hardground
D
Reworking of concretions and hardgrounds, recolonization, renewed sedimentation and burial, mineralization
Leads to formation of TYPE III hardground and buried hiatus concretions

Figure 47. Schematic illustration of the sequence of early diagenetic, biogenic and physical processes leading to the formation of hardgrounds in Middle and Upper Devonian strata in the Hay River area (adapted from Palmer and Fursich, 1974).

Most of the concretions examined in this study appear to be the result of localized centres of early diagenetic cementation with subsequent exhumation, reworking and colonization by boring organisms. This is most evident in the concretions from the lower part of the succession, especially in members A and B of the Fort Simpson Formation. The concretions probably formed by localized, selective cementation of bioturbated sediment . Evidence for this type of cementation is demonstrated by: (1) the formation of cemented burrows preserved in full relief, (2) nodules containing fractures filled by micrite and/or calcite spar, and (3) the formation of type I hardgrounds in close association with nodular limestones.

X. SEDIMENTOLOGY-DEPOSITIONAL HISTORY

A. Introduction

This section attempts to incorporate the descriptions and classifications of rocks and their associated faunas and biogenic and primary physical sedimentary structures, in order to interpret the origin and depositional history of the strata in the study area. The use of the terms transgressive and regressive implies no comment on the cause of the vertical facies arrangements in the study area since transgressions and regressions may result by many processes or combinations thereof, including: changes of sea level, tectonic movement of the sediment-water interface, and deposition of sediment during stable sea level (Wilkinson, 1982); tectonic subsidence and eustatic sea level rise, crustal uplift, subsidence outpaced by a eustatic drop in sea level (Kendall and Schlager, 1981); continental glaciation, mid-plate thermal uplift and submarine volcanism (Johnson *et al.*, 1985)

B. Slave Point Formation

The lithologic and faunal associations at the upper part of the Slave Point Formation are indicative of deposition in a relatively shallow water platform carbonate environment. The fauna consists mainly of dendroid, encrusting and bulbous stromatoporoids, solitary corals, thick shelled brachiopods and ostracodes. Although some of the allochems show signs of having been reworked by currents, most probably accumulated *in situ*.

The regressive, shallow water, tidal flat deposits at the top of the Slave Point Formation contain evidence of nondeposition, omission and/or erosion suggesting that the upper surface of the formation represents a hiatus. Dunbar and Rodgers (1957) outlined three major categories of unconformity; angular unconformity, disconformity, and paraconformity. Of these, only the disconformity and possibly the paraconformity apply to the Slave Point Formation. At the surface of the Slave Point Formation, disconformable surfaces are represented by submarine hardgrounds and, locally, areas where the Slave Point Formation is overlain by strata of the Muskwa Formation. The disconformable nature of this contact is supported by the ostracod zones reported missing by Braun (1968) and Featherstone (1982). In contrast, a paraconformable contact is represented by a gradational contact between the Slave Point Formation and argillaceous strata of the overlying Waterways Formation.

The hiatus, during which the hardgrounds were formed, may have been due to a rapid transgressive pulse which occurred at the end of the Givetian and the start of the early Frasnian (House, 1975a, b; Johnson *et al.*, 1985). The more open marine, interbedded shales and argillaceous limestones of the Waterways Formation were deposited after the hiatus in relatively deeper water.

C. Waterways Formation

The strata of the Waterways Formation were probably deposited during a transgression which followed deposition of the shallow water carbonates of the Slave Point Formation. The relative deepening of the basin at this time is evident by the more open marine nature of the interbedded calcareous shales and argillaceous limestones.

The mottled appearance of many of the limestones and the dearth of recognizable trace fossils reflects a total and repeated biogenic reworking of the sediments, indicative of slow, continuous rates of sedimentation (Howard, 1975; Frey and Howard, 1985). This is further supported by the local abundance of glauconite, which is commonly associated with slow, steady rates of sedimentation (Fürsich *et al.*, 1981).

Based on sediment composition and species composition and richness, Rhoads and Morse (1971) and later Byers (1977) defined three major biofacies in marine environments: (1) aerobic biofacies - dissolved oxygen content greater than 1.0 ml/L (less than 50 m deep), well oxegynated surface waters with a diverse shelly benthic fauna and bioturbation, (2) dysaerobic biofacies - dissolved oxygen content between 0.1 and 1.0 ml/L (50 to 150 m deep), low diversity community with few or no calcareous species, small body size with a dominance of infauna, and (3) anaerobic biofacies - dissolved oxygen content less than 0.1 ml/L (greater than 150 m), shelly benthic fauna and bioturbation lacking, sediment laminated. Byers (1977) applied these biofacies to ancient rocks and discussed the criteria used to recognize them.

A number of workers have modified this model slightly by demonstrating that abundant, low diversity, calcareous faunas can be found in the dysaerobic biofacies (Savrda *et al.*, 1984; Thompson *et al.*, 1985; Kammer *et al.*, 1986).

The limestones and shales of the Waterways Formation were probably deposited under aerobic or dysaerobic conditions in the water column as shown by the complete biogenic reworking of the sediments and the presence of calcareous megafauna such as brachiopods. Lingulid brachiopods are locally preserved in the shales and limestones. Pickerill *et al.* (1984a) documented *in situ* lingulids from deep water, outer shelf and upper slope carbonates in the Middle Ordovician of Newfoundland and Quebec. As noted by Kammer *et al.* (1986) *Lingula* are a common component of relatively deep water dysaerobic faunas in the late Paleozoic.

Sporadic pauses in sedimentation may have led to the formation of localized, discontinuous hardgrounds, which are associated with remnant topographic highs on the surface of the underlying Slave Point Formation. The distribution of the Waterways Formation suggests that it was: (1) not deposited on topographic highs on the surface of the Slave Point Formation, or (2) was eroded from topographic highs before deposition of the strata of the overlying Muskwa Formation. Since no evidence of erosion between the Waterways and Muskwa formations was found in drill core, it would appear that the former is more feasible.

D. Muskwa Formation

The nature of the lower boundary of the Muskwa Formation and the equivalent Canol Formation has been the subject of some controversy. As noted by Williams (1983), workers have been divided into two schools of thought: (1) those favouring an unconformity at the base of the black shales, as a consequence of uplift and subaerial exposure prior to the deposition of the shale, and (2) those favouring a conformable boundary, the result of a rapid transgression and "deepening event". There has also been debate on the environment of deposition of the black shales, a problem which has plagued many workers and is not unique to this area (Dunbar and Rodgers, 1957; Heckel, 1972). Some workers such as Bassett and Stout (1968) suggested that the black shales were deposited in a widespread, shallow, stagnant sea after a sudden transgression covered the entire area. While workers such as Willliams (1977, 1983) argued that the shales had been deposited during a rapid transgression in relatively deep water (on the order of several hundred feet). Commenting on the distribution of bituminous black shales in the rock record, Hallam and Bradshaw (1979) noted that these deposits tend to occur most frequently at or close to the base of sequences deposited during marine transgressions.

The only possible evidence for an unconformable contact at the base of the Muskwa Formation, in the Hay River area, is where the Waterways Formation is absent and the Muskwa Formation overlies the Slave Point Formation. However, as noted previously, this may have been a result of nondeposition as opposed to erosion of the strata of the Waterways Formation. Elsewhere the Muskwa Formation has a sharp and apparently conformable contact with the Waterways Formation. The presence of discontinuous, incompletely developed hardgrounds in the Waterways Formation suggests infrequent periods of omission. However, these features represent localized breaks in the sedimentation and are not indicative of a widespread hiatus during which erosion could have occurred. Based on the available evidence the lower boundary appears to be at most, paraconformable.

The faunal and sedimentological features of the Muskwa Formation are indicative of deposition under anaerobic conditions based on: (1) high organic content as evidenced by the bituminous nature of the shales, (2) presence of abundant beds packed with pelagic *Styliolina* sp. (Fisher, 1962; House, 1975b), (3) fine laminations in the shales, (4) lack of recognizable burrows or any indication of bioturbation, (5) lack of *in situ* calcareous benthic fauna, and (6) the abundance of pyrite asociated with the shales. These features have been documented in modern and ancient black shales by Byers (1977), Cluff (1980), Demaison and Moore (1980), and Sarvda *et al.*, (1984). A similar situation has been reported by Stoakes (1980) for the black bituminous shales and limestones of the Upper Devonian Duvernay Formation. He suggested that they were deposited under anaerobic conditions in relatively shallow water (on the order of 65 m). Stoakes (1980, p. 395) suggested that the anaerobic conditions were the result of "... broad Cooking Lake platform highs and Leduc Reef buildups." which severely restricted water circulation in the basin. In contrast, Mountjoy (1980) suggested that the dark shales of the Upper Devonian Perdrix Formation may have resulted from restricted water circulation in the basin, followed by density stratification of the water column, preventing circulation of bottom waters. Anaerobic conditions may occur in marine environments under the following conditions: (1) upwelling of nutrient rich water creating high levels of biologic productivity, (2) silled basins with a positive water balance (eg. Black Sea) and (3) oxygen minimum layers in the oceans can be produced by stagnation during periods of global warming and transgression (Demaison and Moore, 1980).

The abundance of *Styliolina* sp., concentrated in thin beds in the shales, may be ascribed to a number of origins. It is possible that the these concentrations represent a mass mortality of entire populations. This may have been caused by: (1) a fluctuation of the aerobic-dysaerobic boundary in the water column (Kammer *et al.*, 1986), (2) a rising H_2S /O_2 interface in the water column, which when reaches the euphotic zone leads to mass mortality (Berry and Wilde, 1978; Wetzel, 1982), and (3) individuals reach a certain body mass and exceed their oxygen requirements (Kammer *et al.* 1986). Similar concentrations of styliolines in black shales have been documented from the Devonian Genesco Shale of New York by (Heckel, 1972). He suggested that this fauna is typical of black shales deposited in a stagnant marine basin. The presence of *Lingula* sp. concentrated locally in the shales might also suggest a fluctuating anaerobic-dysaerobic boundary. As noted by Kammer *et al.* (1986), *Lingula* are common in deep water dysaerobic faunas in the late Paleozoic.

The widespread event which was responsible for the stagnant aerobic conditions under which the black bituminous shales of the Muskwa Formation were deposited, was followed by more oxygenated conditions in the basin. During this time more open marine calcareous shales and limestones of the Fort Simpson Formation prograded into and started to fill the basin.

E. Fort Simpson Formation

Most of the Fort Simpson Formation comprises calcareous grey to green grey shales. Near the base and top of the formation thin limestone beds and quartzose limestone and calcareous siltstone beds are common, respectively. The distribution, geometry and composition of these beds provide useful indications of the history of sea level fluctuations and other controls on deposition affecting the basin.

The open marine shales and argillaceous limestones near the base of the Fort Simpson Formation are similar in composition and geometry to those documented from the Ireton Formation by McCrossan (1961), Oliver and Cowper (1963), Stoakes (1980) and Cutler (1983). Based on the presence of sloping carbonate log markers in the thick shale package, the sediments of the Ireton Formation are thought to have been deposited in a progradational manner as a series of wedge shaped, sigmoidal, "depo-units" (Stoakes, 1980). These overlap each other and are imbricated basinward. Stoakes (1980) concluded that deposition of these units occurred during a net rise in sea level in water depths of 100 to 105 m, based on the preserved depositional topography of the marker beds. Similar features have been observed in the subsurface of the Hay River area by Williams (1977). Very gently sloping limestone beds occur in the shales of the Fort Simson Formation but, due to the relatively small size of the study area, it was impossible to determine the extent and geometry of these bodies in relation to each other. Angular values of slope were calculated for the limestone bed at the top of member A of the Fort Simpson Formation. Slopes on this bed are 10 to 15 cm/ km, giving angular values of less than 1°. It is quite likely that precompactional values of slope may have been greater. Similar values of depositional slope have been determined for an ancient carbonate ramp in the Late Silurian-Early Devonian Helderberg Group by Dorobek and Read (1986). In contrast, markers in the Ireton Formation have slopes of 3 to 9 m/km (Oliver and Cowper, 1963), 4 to 7 m/km (Stoakes, 1980). Williams (1977) reported values of 6 m/km for slopes of geophysical log markers in the Hay River Formation. The low angles of slope of the log markers and the lack of deformation or gravitational slump features in the Upper Devonian strata in the Hay River area suggests that deposition occurred on a gently sloping ramp (Ahr, 1973; Read, 1985; Aigner, 1985).

The strata of member A of the Fort Simpson Formation probably record a steady increase in carbonate sedimentation during a slow, steady rise in sea level. Shales at the base of the member grade upward into shale with interbeds of argillaceous limestone. The number and thickness of the interbeds increases toward the top of the member. The uppermost limestone bed is marked by the presence of a widespread hardground. This bed forms a very gently sloping marker in the study area and can be traced for many kilometres outside the study area. The hardground at the top of member A was probably formed during a pause in sedimentation. A similar mode of genesis has been suggested for sloping carbonate beds in Upper Devonian shales in other parts of the Western Canadian Basin by Mountjoy (1980) and Stoakes (1980). The incomplete nature of the hardground (ie. lack of colonization by borers and encrusters etc.) might suggest a relatively short period of omission only, without a long hiatus. Consequently, the widespread hardground at the top of member A may represent a synchronous marker. However there is no detailed paleontological evidence which could confirm this and caution must be excersised, since there is evidence to suggest that in some cases submarine cementation and hardgrounds may be diachronous (Purser, 1969). The use of such markers as essentially synchronous time lines has been recognized by numerous workers (Rose, 1970; Hattin, 1971; Wilson, 1975; Mountjoy, 1980; Stoakes, 1980; Schultz, 1982; Miall, 1984).

The carbonates at the top of member A were probably deposited under relatively slow and continuous rates of sedimentation in a manner similar to those of the Waterways Formation. Some of the material in the limestones appears to have been reworked. This is especially true of the allochems which consist mainly of disarticulated brachiopods and crinoid ossicles. Much of the fine carbonate fraction may have been derived from suspension (James, 1984) and/or sea floor diagenesis (Eder, 1982; Walther, 1982). Early diagenetic cementation, in conjunction with biologic reworking and bottom currents, appears to have controlled the development of limestone nodules in the shale as well as the nodular appearance of the limestone beds. This is shown by: (1) lithified burrow fills preserved in full relief as nodules, (2) small spar or micrite filled cracks in the nodules, (3) nodular appearance of limestone beds which are commonly intensely to completely bioturbated, (4) fine argillaceous seams and microlaminae which warp around some nodules (probably related to post depositional compaction), and (5) the presence of hardgrounds in the limestones. Similar early diagenetic features have been documented in ancient rocks by Noble and Howells (1974), Kennedy and Garrison (1975a, b), Jones *et al.* (1979), Baird (1978, 1981) and from modern carbonate environments by Mullins *et al.* (1980).

The break in sedimentation responsible for the hardground at the top of member A was followed by a renewal of slow, continuous rates of sedimentation during which time shales with thin limestone beds and abundant mudstone nodules of member B were deposited. These lithologies may represent a more distal equivalent of the underlying member A. This supposition is based on the fact that the limestone beds in member B are concentrated mainly in the lower part, are very thin in comparison to those of member A, and commonly contain abundant black bored hiatus concretions. The concretions show evidence of early selective, diagenetic cementation, exhumation, colonization by borers and reburial. Baird (1981) documented similar concretions from gentle paleoslopes in the Devonian of New York. Alternatively these may represent the remnants of reworked submarine hardgrounds similar to those found at the top of member A. If these beds were deposited during a continued rise in sea level it might follow that there was a relative shoreward shift in facies during this time.

Member C is relatively homogeneous in lithology, consisting mainly of green grey calcareous shale and calcareous mudrock. Unlike the members above and below it is conspicuous by its lack of thin carbonate beds. A fairly widespread unit of thinly interlaminated black, noncalcareous shale and grey, calcareous shale occurs near the base of member B. Similar to the Muskwa Formation, but on a more limited scale, this unit might indicate a pause in sedimentation during a period of stagnation, under low energy conditions.

This is supported by the lack of calcareous benthic fauna, fine laminations, lack of bioturbation and the dark colour and noncalcareous nature of the black shale laminae. The interlaminated appearance of the rock might indicate an episodic, cyclical style of sedimentation. The overlying calcareous shales and mudrocks represent an increase in carbonate sedimentation, probably from suspension, since these beds lack transported skeletal material. These lithologies appear to record progressive infill but with a possible further shifting of facies shoreward, during continued slow sea level rise. The strata of members A to C possibly represent an onlap type of sedimentation (Mountjoy, 1980; James and Mountjoy, 1983) where there is a gradual retreat of shallow water facies shelfward, over older platform deposits. This situation appears to arise when sedimentation can not keep pace with relative sea level rise (James and Mountjoy, 1983).

The lithologies of member D of the Fort Simpson Formation record a dramatic change in the style of sedimentation in the basin. Member D contains a number of calcareous siltstone, quartzose and bioclastic limestone beds. In addition, shales in the member also contain detrital quartz. These rocks record the first major influx of terrigenous quartz to the basin, in this area. The very fine sand to coarse silt size quartz in these rocks may have been derived by a number of processes including: (1) shore derived terrigenous clastics, trapped by higher shorelines may prograde basinward, especially during still stands or regressive phases (Stoakes, 1980; Mountjoy, 1980), (2) deposition of fine terrigenous material by aeolian processes (Shinn, 1973, 1983; Mount, 1984), (3) transport of tidal flat and shore siliciclastic belt sediments into deeper subtidal environments by storm-surge-ebb, wind forcing (Kreisa, 1981; Tucker, 1982; Mount, 1984).

A well preserved assemblage of trace fossils are preseved in the carbonates and mixed carbonate and siliciclastic beds of member D. The lower boundary of the member is formed by a completely bioturbated, calcareous siltstone bed containg *Rhizocorallium jenense* Zenker and *Planolites beverleyensis* Billings. These essentially horizontal traces might represent the reworking of sediments by deposit feeding organisms (Fürsich, 1974; Basan and Scott, 1979;

Pickerill *et al.*, 1984a) and are probably referable to the *Cruziana* ichnofacies of (Seilacher, 1967). This ichnofacies is most characteristic of subtidal, poorly sorted, unconsolidated substrates (Frey and Pemberton, 1984).

Towards the middle part of the member, a number of the quartzose beds contain a diverse assemblage of traces including, *Planolites beverlyenesis* Billings, *Skolithos linearis* Haldeman, *Diplocraterion parallelum* Torrell, *Monacraterion tentaculatum* Torrell, *Arenicolites*? *variablis* Fürsich, *Chondrites sp.*, *Tricophycus sp.*, *Rhizocorallium sp.*, *Munsteria*? *sp., and Phycodes*? *sp.* Most of the traces are relatively sharp walled, unlined, and do not cross cut grains or cement. The sharp walls and the excellent preservation of the traces possibly indicates burrowing in stable, firm, cohesive sediment (Frey, 1975; Ekdale *et al.*, 1984; Frey and Pemberton, 1984). These traces are most likely assignable to the *Glossifungites* ichnofacies which represents burrows in firm but unlithified substrates (Frey and Pemberton, 1984). Originally Seilacher (1967) defined the *Glossifungites* ichnofacies to cover "hard" substrates of the littoral zone (as distinguished form the soft, freely shifting, littoral substrates of the *Skolithos* ichnofacies). Frey and Seilacher (1980) subsequently redefined this definition to apply only to firm but uncemented surfaces and reserved the *Trypanites* ichnofacies for fully lithified substrates. The traces in the beds in member D were probably made primarily by deposit feeding organisms. As noted by Frey and Pemberton (1984), substrate firmness precludes most intrastratal deposit feeding.

A number of the thin limestone beds and quartzose limestone beds in member D contain features indicative of deposition by sporadic, high energy events. These are most probably storm deposits as indicated by: (1) erosional and scoured bases, commonly with multidirectional tool marks on the soles of beds (Kreisa, 1981; Aigner, 1982, 1985; Bloos, 1982; Kreisa and Bambach, 1982), (2) coarse skeletal material concentrated above the erosive base, commonly fining upward (Kreisa, 1981; Aigner, 1982), (3) disarticulated brachiopod shells commonly oriented convex-up, forming shelter structures containing calcite spar or micritic sediments (Jones and Dixon, 1976; Kreisa, 1981; Aigner, 1982, 1985; Kreisa and

Bambach, 1982), (4) skeletal lag overlain by planar to undulose to cross-laminated quartzose limestone (Kreisa, 1981; Aigner, 1982; Kreisa and Bambach, 1982), (5) the laminated unit is commonly bioturbated (Kreisa and Bambach, 1982, Fürsich, 1982; Seilacher, 1982; Aigner, 1982; Wu, 1982; Handford, 1986). Preservation of all of these features in a bed constitutes an ideal tempestite sequence (Aigner, 1985). Similar to the widespread hardground at the top of member A, these tempestites might be considered to have been a relatively instantaneous event and thus represent time lines. The use of events as time lines has been demonstrated by Krumbein and Sloss (1963), Ager (1973) and Dixon *et al.* (1981).

In one case the laminated unit above the shell lag contained a trace fossil assemblage consisting of *Planolites beverleyenesis* Billings, *Diplocraterion parallelum* Torrell, *Cylindrichnus concentricus* Howard, *Skolithos linearis* Haldeman, and *Palaeophycus tubularis* Hall. These traces show trace-sediment relations similar to those in the firmgrounds. They probably represent biological colonization ("post-event colonization") following the storm event (Aigner, 1985). Some of these traces may represent escape structures (e.g. *Skolithos linearis* Hall) where laminations are distorted (Schäfer, 1972), while others probably represent the activities of suspension feeding organisms. Some of the traces such as *Palaeophycus tubularis* Hall probably represent the activities of deposit feeders. Pemberton and Frey (1982) suggested that *Palaeophycus* represents passive sedimentation in an ephemeral burrow constructed by a mobile deposit feeder. A relatively analogous assemblage, consisting of shallow *Chondrites* spp. and *Palaeophycus tubularis* and deeper filter feeding traces of *Planolites* sp. and *Skolithos linearis*, was documented by Pickerill *et al.* (1984b) in offshore storm produced skeletal calcarenites in the Ordovician Trenton Group.

Aigner (1985) noted that storm effects decrease toward deeper offshore bottoms and that this should produce a lateral succession of bedforms in tempestites, similar to turbidites, which range between proximal and distal end members. Some of the "ideal sequences" that occur in member D are almost identical to the proximal tempestites described by Aigner (1985) from the Triassic Upper Muschelkalk of Germany. Aigner (1985) suggested that the vertical succession of structures in the "ideal sequence" indicates deposition from a waning flow with a complex interaction of oscillatory and unidirectional flows. He noted that such combined flows can be expected when storm waves touch the sea floor and interact with unidirectional (e.g. gradient) currents.

In contrast, some of the very thin limestone beds containing skeletal material or other allochems only, may be indicative of more distal deposition. The mode of occurrence of the thin beds in calcareous shales suggests that background sedimentation was episodically interrupted by storm generated energy peaks causing erosion, suspension and resedimentation of detritus (Aigner, 1979).

The occurrence in member D of a well developed bored and encrusted hardground and associated hiatus concretions and/or reworked hardgrounds might also be related to the effects of storm generated currents. This type of current may act to remove material, exhuming underlying lithified material which could act as a firm- or hardground suitable for specific burrowers, borers or encrusters, or even break it up to form reworked hardgrounds (Aigner, 1979, 1982, Aigner *et al.* 1978; Fürsich, 1982). Sprecht and Brenner (1979) suggested such a mechanism for the formation and distribution of encrusted and bored perigenic carbonate nodules in the Upper Jurassic of Wyoming. The close association of hardgrounds and firmgrounds has been alluded to by Frey and Seilacher (1980), Frey and Pemberton (1984) and Pemberton and Frey (1985) who noted that the *Glossifungites* and *Trypanites* ichnofacies tend to be somewhat intergradational.

Locally, at the upper part of member D, mottled maroon and green grey silty, calcareous shales are common. The mottled appearance appears to be the result of intense bioturbation of the shales, although no identifiable traces could be recognized. Similar maroon and grey shales occur in the upper part of the Ireton Formation. These are thought to represent deposition in supratidal to intertidal environments (Stoakes, 1980) or possible proximity to a shoreline (Belyea, 1955). However, as Potter *et al.* (1980) have pointed out, the controls on the colour of shales are still poorly understoood. They suggested that colour is controlled mainly by the content of organic carbon and Fe^{3+}.

The presence of well developed firmgrounds, hardgrounds, and tempestites in the shales of member D seems to indicate a relatively shallow water environment of deposition in comparison to the underlying members. It is tempting to suggest an environment in relationship to "fair weather" and "storm wave base". However, the depth of wave reworking on modern shelves shows strong seasonal variations (wave base during winter storms may be twice as deep as during the summer), therefore, there seems to be a continuous spectrum of conditions, suggesting that the terms "fair weather" and "storm wave base" are probably rather artificial categories (Aigner, 1985).

There seems to have been a relative shallowing, possibly due to a regressive phase or possibly to a stillstand, during which time more shoreward facies of member D prograded basinward. The lateral shifting of facies in the basin-filling strata might be explained by the low slopes on the depositional surface. Dorobek and Read (1986) suggested that because of low values of slope on a ramp like topography, sediment distribution patterns may be drastically affected by slight changes in sea level.

F. Escarpment Formation

The Escarpment Formation consists mainly of various shales with relatively thick, bedded units of argillaceous limestone and mixed carbonate-siliciclastics. These units increase in thickness and abundance toward the top of the formation, at the expense of the shale. This sequence appears to record a cyclic style of sedimentation with a general shallowing upward trend. The cyclicity of the sequence is shown by alternations of argillaceous, bioturbated limestones, containing abundant benthic organisms, with unfossiliferous, current bedded, carbonate-siliciclastic units. This cyclicity indicates that there may have been sporadic influxes of terrigenous quartz to the basin, interrupting carbonate production, the growth of benthic organisms, and background sedimentation. During times of reduced terrigenous quartz influx, carbonate sedimentation resumed and benthic communities colonized the sea floor. In contrast to the carbonate beds in the underlying strata, those in the Escarpment Formation contain an abundant and diverse fauna of brachiopods, corals, stromatoporoids and some gastropods and goniatites. In a number of cases these organisms are arranged in an organic framework, forming biostromal and, locally, biohermal units. These represent early attempts to colonize the sea floor, probably in relatively shallow subtidal conditions.

The lower boundary of the Escarpment Formation is marked by a sharp based, calcareous sandstone-siltstone bed, with an asymmetrical ripple marked surface. It contains a high density of traces fossils, including; *Palaeophycus striatus* Hall, *Planolites montanus* Richter, *Tricophycus* sp., *Diplocraterion* sp., and *Thalassinoides* sp. The ripplemarks are indicative of current bedding, however, these features are known to form in beach environments to deep water environments (Boggs, 1987). In comparison, this bed is similar to the storm deposited beds in member D of the Fort Simpson Formation and may have been deposited in a similar fashion. The trace fossil asemblage is well preserved and individual traces have sharp, undeformed walls, indicating that burrowing probably occurred in firm sediment. These traces are probably assignable to the *Glossifungites* ichnofacies. The majority of the traces appear to be the result of deposit feeding and are comparable to the *Diplocraterion* association documented by Fürsich (1975) in Upper Jurassic limestones deposited in high energy environments.

The ripple marked bed is overlain by a thick, crudely bedded, highly fossiliferous, argillaceous limestone unit. It is completely biotubated, giving it a rubbly weathered appearance, and contains a normal marine fauna including, brachiopods, horn corals, goniatites, stromatoporoids and domal and encrusting corals. The complete biologic reworking and abundant benthic fauna may indicate relatively slow, continuous rates of sedimentation.

The rate of terrigenous quartz influx to the basin appears to have been sporadic. This is shown by comparison of the relatively thick calcareous siltstone near the middle of member A and the relatively thinner calcareous sandstone at the base of member B. Both units are unfossiliferous. The thick unit in member A is intensely to completely bioturbated with only minor remnants of the original physical sedimentary structures, indicating possible slow steady rates of sedimentation. In contrast, the siliciclastic unit at the base of member B contains fine planar to undulose laminations, cross-laminations, scour structures, truncated bedding and vertical *Skolithos* sp., which in many case are truncated by overlying beds. These features suggest relatively more rapid, episodic rates of sedimentation, punctuated by erosive events.

A thin oolite bed, correlatable over a distance of 3.75 km, occurs near the top of member A of the Escarpment Formation and may be indicative of deposition in a shallow, high energy environment (Bathurst, 1975; Flügel, 1982; Richter, 1983). Although shallow water ooids can be transported to deep water (Andrews *et al.*, 1970), these radial and radial concentric ooids appear to have formed *in situ* since they show no signs of abrasion or reworking. Purely radial ooids may form in relatively deep water, downslope from carbonate platforms, in areas where the sea is weakly agitated and saturated with respect to $CaCO_3$ (Heller *et al.*, 1980; Reijers and ten Have, 1983). The ooids in member A contain a radial inner cortex and, in many cases, concentric radial banding. Heller *et al.* (1980) interpreted this composite fabric in terms of variable hydrodynamic behavior. Radial crystal growth reflects periods of weak agitation in which the small ooid resides predominantly in suspension, while concentric layers represent increased agitation, possibly as a result of slightly regressive conditions, during which the grain rolls about and concentric layers are added.

Upward in the section, such as at the top of member B and locally in members C and D, limestone units are dominated by encrusting and tabular stromatoporoids and domal and encrusting corals (mainly *Alveolites* sp. and *Phillipsastrea* sp.), with lesser amounts of brachiopods, crinoids, horn corals and gastropods. These units exhibit a biostromal and, locally, a biohermal appearance. The matrix of the bindstones commonly consists of mudstone to wackestone. Fossiliferous grainstones to rudstones occur in cose association with these biostromes.

As noted by James (1984) certain generalizations can be made about the form and environments of reef building organisms. The majority of the corals and stromatoporoids in the bindstones, consist of tabular, encrusting and low domal to irregular forms. In general, these forms are indicative of moderate to intense wave or current energies with relatively low rates of sedimentation (James, 1984). However, as Stearn (1982) suggested, the shapes of reef organisms are not specific guides to environments of modern reefs and should not be expected to be guides for ancient ones. A review of the shape zonation on modern reefs indicates that no general pattern is applicable to all reefs and that variations in shape are the result of many environmental factors and the genetically dictated growth patterns of corals (Stearn, 1982).

Stromatoporoids are common on open marine shelf deposits in the Devonian of western Canada and were adapted for life in seas floored by soft sediments and subjected to moderate currents (Murray, 1966; Leavitt, 1968; Jamieson, 1971). As noted by Jamieson (1971), *Alveolites* is most commonly found in "protoreef" and proximal backreef lithologies and appears to have been an effective sediment stabilizer because of its encrusting growth habit. Observations of *Alveolites* in Givetian and Frasnian reefs indicates a tolerance for moderate amounts of argillaceous material in open marine environments of moderate depth and turbulence (Klovan, 1964; McCamis and Griffith, 1967; Jamieson, 1971). *Phillipsastrea* dominates the "protoreef" communities and some back reef patches, but is rare elsewhere (Jamieson, 1971). Like *Alveolites*, *Phillipsastrea* apparently favoured waters of moderate depth and turbulence (Klovan, 1964; Wilson, 1967; Jamieson, 1971). Solitary corals are volumetrically insignificant and appear to have been incidental reef dwellers, similar to other Devonian reefs in western Canada (Klovan, 1964; Jenik and Lerbekmo, 1968; Leavitt, 1968; Fischbuch, 1968; Jamieson, 1971). Brachiopods are abundant in the limestone beds and rare in the mixed carbonate-siliciclastic beds. They are represented by a large number of taxa and individuals. Analagous brachiopod communities have been described from the Upper Devonian of New York by Thayer (1974). He noted a *Schizophoria*-strophomenid biofacies, characterized by fauna adapted to life on a soft, fine grained bottom which accumulated during periods of reduced clastic influx.

It appears that the organisms forming the biostromal units record periods of intense colonization of the sea floor. During these intervals, terrigenous quartz influx must have been minimal or nonexistant, allowing widespread colonization of suspension feeding organisms. The development of these relatively continous, low relief, thin biostromal units might be related to a number of factors, the most important of which seems to be cessation of terrigenous influx. Heckel (1974) noted that terrigenous influx and catastrophic storms frequently interupt organic growth in nearshore environments and, therefore, the intense organic activity required for building and binding rigid masses are maintained only for sufficient time to produce small buildups. In addition, with sediment production at a rate much greater than that needed to compensate for subsidence, buildups may grow laterally. On sloping, even bottoms, all of the bottom may be favourable for sufficient organic proliferation to keep up with subsidence (Heckel, 1974). In some cases the biostromal units grade basinward into bioturbated wackestones, possibly indicating unfavourable conditions for growth in this direction. Locally, such as in the middle of member D, biostromal units have some topographic relief and exhibit a biohermal nature, indicating that in some areas conditions may have been more favourable for organic growth and proliferation.

Relatively shallow water, low to moderate energy environments are indicated for deposition of the bindstones in the upper part of the Escarpment Formation by (1) the low relief and encrusting growth forms of the organisms, (2) the crudely bedded deposits of fossiliferous grainstones which underlie and commonly ocur within the biostromal units, (3) the localized biohermal nature of some of these units, and (4) the localized presence of hardgrounds, commonly containing *Trypanites*. Similar relationships have been documented from the Helderberg Group of the central Appalachians by Dorobek and Read (1986). Paleoenvironmental analysis of the Escarpment Member (=Escarpment Formation) led Mitchell (1970) to conclude that these units were deposited in a high energy inner sublittoral environment.

The thick, cliff forming sequence of thinly interbedded limestone and shale of member D represents a dramatic change in the style of sedimentation in the area. The most characteristic feature of these beds is the homogeneity of their composition and their lack of physical sedimentary structures. They are intensely to completely bioturbated with deposit feeding traces of *Chondrites* sp. and *Teichichnus* sp. preserved locally. *Teichichnus-Chondrites* assemblages are common in shallow to medium bathymetric ranges in chalk deposits (Ekdale *et al.*, 1984). In Upper Jurassic limestones of England and Normandy, Fürsich (1975) noted that *Teichichnus* is characterisic of nearshore subtidal areas of reduced turbulence and current activity as well as lagoons, but that it is related mainly to hydrodynamic conditions and only indirectly to depth. Aigner (1985) documented *Teichichnus* dominated assemblages from transitional areas between shallow and deep water ramp deposits in the Triassic Muschelkalk. Benthic organisms in the limestones of member D consist mainly of brachiopods and gastropods. The argillaceous content and thickness and number of shaley interbeds increases basinward while the total thickness of the bedded sequence decreases. These features seem to suggest slow steady rates of carbonate sedimentation, punctuated by periodic influxes of argillaceous material. The total reworking of the sediments by deposit feeding organisms and the thinly bedded nature of the sequence seem to indicate deposition in a relatively quiet environment.

The cyclic nature of the the interbedded limestones and shales suggests that carbonate deposition was periodically interrupted by events which produced bedding planes and/or shale interbeds. The thinly bedded sequence of member D resembles limestone sequences described by Schwarzacher and Fischer (1982), Ricken and Hemblen (1982) and Bausch *et al.* (1982). Carbonate material may have been of local biogenic origin or from nearby carbonate buildups. The alternating cycles might possibly be due to fluctuations in sea level. For example, a drop in sea level may have increased the influx of terrigenous material, while reducing the supply of carbonate (Schwarzacher and Fisher, 1982). Alternatively, changes in climatic conditions and wind driven currents may also have been important. As opposed to variations in the primary delivery of carbonate and terrigenous material, the cyclic bedding may have originated by early diagenetic redistribution of carbonate material (Eder, 1982; Walther, 1982).

The composition, bedding patterns, fauna and trace fossils in the limestones of member D are comparable to the deep and transitional ramp zones of the Triassic Muschelkalk as described by Aigner (1985). They appear to be the result of deposition in a relatively low energy environment. Mitchell (1970) suggested that these beds were deposited in a low energy sublittoral environment.

The deposition of the interbedded limestones and shales of member D was interupted by deposition of calcareous shales which form the base of member E. Terrigenous quartz influx to the basin increased slowly, resulting in a thin interbedding of calcareous sandstone and shale in the overlying transitional zone. This was followed by increased rates of quartz influx resulting in the deposition of a prograding deposit of laminated to cross-laminated sandstones with some shaley interbeds and laminae. These beds were probably deposited under higher energy conditions than the limestones of member D as shown by the cross-laminations and abundant vertical traces of *Skolithos* sp. Deposit feeding traces of *Chondrites* sp. and *Planolites* sp. are also abundant. In some cases vertical traces are truncated by overlying beds indicating episodic erosive events. Trace fossils are commonly deformed indicating that burrowing took place in soft sediments, however, traces of *Scolicia* sp. and *Uchirites* sp. are locally well preserved, showing fine appendage marks, possibly made by arthropods. These traces are indicative of more stable, firm substrates (pers. comm. S. G. Pemberton, 1987). Narbonne (1984) documented a *Fuersichnus-Uchirites* assemblage in limestones deposited in a shallow subtidal shelf environment from the Silurian of Arctic Canada. Jamieson (1968) considered the calcareous sandstones to represent sublittoral and littoral deposits of a coastal plain environment which progaded from the east or northeast.

The regressive progradation of relatively shallow water sediments into the basin continued as shallow water, highly fossiliferous limestones of the Alexandra Member were deposited.

G. Alexandra Member (Twin Falls Formation)

The nodular to laminated limestones and dolomitic limestones of the Alexandra Member, which overlie the sandstones at the top of the Escarpment Formation, represent continued deposition in relatively shallow water. The influx of detrital quartz to the basin decreased after deposition of the sandstones of member E. The overlying bedded fossiliferous limestones record the successful development of a widespread organic reef complex, relatively free from terrigenous quartzose and argillaceous material (Jamieson, 1971). The bedded lagoonal lithologies exposed in the Hay River Gorge, developed in the Late Frasnian along a northward extension of the Grosmont Shelf. The rocks of the Alexandra Member record the development of a shallow water reef complex which passes upward from reef to lagoon to restricted and intertidal mudflat deposits (Jamieson, 1971).

H. Summary

The Upper Devonian strata in the Hay River area appear to record a major transgression and regression with deposition taking place on a gently sloping ramp. A hiatus, which followed deposition of shallow water platform carbonates of the Slave Point Formation, resulted in the formation of a bored and encrusted hardground (Fig. 48). A major transgression followed the hiatus, resulting in slow continuous rates of sedimentation and the deposition of open marine calcareous shales and limestones of the Waterways Formation (Fig. 48). Following this, widespread, stagnant conditions developed, possibly as circulation in the basin became restricted. During this time black, organic rich shales of the Muskwa Formation were deposited (Fig. 48).

During a continued transgressive pulse, circulation was reestablished and deposition of open marine shales and carbonates resumed and widespread carbonate beds, at the top of member A of the Fort Simpson Formation, were deposited by a combination of slow steady rates of sedimentation, biologic reworking and early diagenetic cementation. A pause in sedimentation resulted in the formation of a widespread hardground in the limestone bed at the top of member A. During a continued transgressive phase deeper ramp lithologies were

Formation - Member		**Lithology**	**Fauna**	**Environment**	
Alexandra Mbr. Twin Falls Fm.		fossiliferous, nodular, laminated limestones	corals, stromatoporoids, crinoids, brachiopods, gastropods	shallow water, reef, lagoon, tidal flat	**REGRESSION**
Escarpment Fm.	member E	calcareous, current bedded sandstone, interbedded shale and sandstone, shale	deposit feeders, *Chondrites*, *Planolites*, arthropods, *Scolicia*, *Uchirites* *Skolithos*	prograding shallow ramp lithologies, shallow subtidal, high energy	
	member D	thin bedded mudstones, with very thin shale interbeds, bioturbated	brachiopods, gastropods, deposit feeders *Teichichnus*, *Chondrites*	restricted, quiet water conditions, deeper ramp ?	
	member C	calcareous shale, thin interbeds of mudstone to calcareous siltstone, biostromal limestone	brachiopods, some corals, stromatoporoids, gastropods, crinoids	shallow subtidal, prograding shallow ramp lithologies	
	member B	calcareous shale, thick interbeds of calcareous current bedded sandstone, biostromal limestone localized hardgrounds	corals, stromatoporoids, brachiopods, crinoids, gastropods, goniatites, *Skolithos*	shallow subtidal, prograding shallow ramp lithologies	
	member A	calcareous shale, thick interbeds of bioturbated calcareous siltstone and fossiliferous limestone localized hardgrounds	corals, stromatoporoids, brachiopods, crinoids, gastropods, goniatites	shallow subtidal, prograding shallow ramp lithologies	
Fort Simpson Fm.	member D	calcareous to silty shales, interbeds current bedded, calcareous siltstones bioclastic tempestites, firmgrounds, hardgrounds	deposit and suspension feedersof the *Glossifungites* and *Trypanites* ichnofacies encrusting corals, serpulids	shallow to transitional ramp, subtidal, above storm wave base, storm influence	
	member C	calcareous shale and mudrock, dark noncalcareous shale near base of member	none to rare brachiopods	deep subtidal, below storm wave base, deep ramp or basinal lithologies	**TRANSGRESSION**
	member B	calcareous shale with limestone nodules, rare thin limestone beds near base, hiatus concretions	rare brachiopods	deep subtidal (deeper than A)	
	member A	calcareous shales, some limestone nodules, interbeds of bioturbated, argillaceous mudstone to wackestone at top, widespread hardground	brachiopods, ostracodes, crinoid ossicles	deep subtidal, deep to transitional ramp lithologies	
Muskwa Fm.		black, bituminous shale, siliceous, pyrite ubiquitous	styliolines, *Lingula*	deep subtidal, stagnant, anaerobic conditions	
Waterways Fm.		argillaceous, bioturbated mudstones to wackestones, glauconitic, interbedded with calcareous shale, localized hardgrounds	brachiopods, ostracodes crinoid ossicles	deep subtidal (below storm wave base ?)	
Slave Point Fm.		mudstones to bindstones, bored hardground at upper surface	stromatoporoids, corals, brachiopods ostracodes	shallow water, subtidal to tidal	

Figure 48. Generalized summary of the depositional history of strata in the study area.

successively deposited over relatively shallower ramp lithologies as shown by the lack of carbonate beds and benthic fauna in the shales and mudrocks of members B and C of the Fort Simpson Formation (Fig. 48).

The strata of member D of the Fort Simpson Formation record a drastic change in the style of sedimentation in the basin. At this time deposition was controlled by regressive conditions, with relatively shallower ramp lithologies prograding basinward over deep water ramp lithologies. These rocks record the first influx of detrital sand and silt size quartz to the basin, much of which was transported and deposited by storms (Fig. 48). Thin limestone and mixed carbonate-siliciclastic beds in member D are characterized by the occurrence of tempestites, firmgrounds, and bored and encrusted hardgrounds.

The progradation of shallow water ramp lithologies in a basinward direction continued with the deposition of a the cyclic sequence of limestones, mixed carbonate-siliciclastics and shales which comprise the Escarpment Formation (Fig. 48). During periods of reduced terrigenous influx the soft seafloor was colonized by a diverse and abundant assemblage of brachiopods, stromatoporoids, corals, crinoids, and goniatites. Locally, these organisms created loose frameworks of coral-stromatoporid bindstones, with biostromal and, locally, biohermal morphologies.

This was followed by a relative period of quiescence during which the thick sequence of thinly interbedded limestones and shales of member D were deposited. Progradation of shallow water lithologies continued and, under relatively higher energy conditions, the calcareous sandstones of member E were deposited. Conditions stabilized, the influx of terrigenous quartz and fine argillaceous material to the basin ceased, calcareous metazoans flourished and the extensive reef complex of the Alexandra Member developed (Fig. 48).

XI. CONCLUSIONS

1. Upper Devonian strata in the Hay River area, previously referred to the Hay River Formation, can be divided into four formations: the Waterways, Muskwa, Fort Simpson and Escarpment formations. The Fort Simpson Formation can be subdivided into four members, A to D and the Escarpment Formation into five members, A to E.
2. Interbedded bioturbated, argillaceous limestones and calcareous shales of the Waterways Formation disconformably and, locally paraconformably, overlie shallow water limestones of the Slave Point Formation. Disconformable surfaces are represented by hardgrounds, which formed on topographic highs at the upper boundary of the Slave Point Formation. Strata of the Waterways Formation represent slow, steady rates of sedimentation during a transgression. They are absent, locally, due to nondeposition on topographic highs on the underlying Slave Point Formation.
3. Black bituminous shales of the Muskwa Formation conformably overlie the Waterways Formation and, locally, the Slave Point Formation. They record a period of stagnation in the basin during which time black, organic rich sediments were deposited under anaerobic conditions.
4. Strata of the Fort Simpson and Escarpment formations were deposited on a gently sloping ramp (less than 1° of slope). Relatively deep water deposits of the Fort Simpson Formation prograded shoreward during a transgression, while relatively shallow water deposits of the Escarpment Formation prograded basinward during a regression.
5. With increased circulation in the basin and continued transgression, open marine shales with some limestone interbeds of the Fort Simpson Formation were deposited. Bioturbated, argillaceous limestone beds at the top of member A of the Fort Simpson Formation represent slow, steady rates of sedimentation in a deep subtidal environment. A combination of currents, bioturbation and early cementation led to the formation of

limestone nodules in shale, the development of nodular limestones and the formation, during a period of omission, of a widespread hardground at the top of member A. The calcareous shales of members B and C represent deposition in slightly deeper water.

6. Strata of member D of the Fort Simpson Formation record a dramatic change in the style of sedimentation in the basin during a regression. Storms played a major role in sedimentation by reworking terrigenous quartz basinward and forming current bedded calcareous siltstones, tempestites, hardgrounds, reworked hardgrounds, and firmgrounds. These beds contain a diverse assemblage of trace fossils made by a variety of suspension and deposit feeding organisms and were deposited in subtidal conditions above storm wave base.

7. Thickly interbedded, shale, fossiliferous limestone and mixed carbonate-siliciclastic units of the Escarpment Formation were deposited under subtidal conditions as a shallow water ramp prograded basinward. Strata of the Escarpment Formation represent a cyclic style of sedimentation. During periods of reduced clastic influx the soft bottom was colonized by a diverse benthic community dominated by brachiopods, crinoids, corals, and stromatoporoids which locally formed extensive biostromal to biohermal deposits. The thick sequence of thinly interbedded mudstones and shales, of member D, were deposited under more restricted, quiet water conditions. The calcareous, current bedded sandstones at the top of member E were deposited in a shallow subtidal environment.

8. Cessation of terrigenous clastic influx to the basin allowed proliferation of reef building organisms and the deposition of shallow water fossiliferous limestones representing the reef complex, lagoon and tidal flat deposits of the Alexandra Member of the Twin Falls Formation.

9. Hardgrounds occur at or near the upper surface of the Slave Point Formation, at a number of levels in the Waterways Formation, near the top and bottom of the Fort Simpson Formation and at a number of levels in the Escarpment Formation. The most widespread

of these occurs in a gently sloping argillaceous limestone bed at the top of member A of the Fort Simpson Formation and covers an area of 400 km^2.

10. Three types of hardgrounds occur in these strata: type I, simple hardgrounds; type II, bored hardgrounds; and type III, bored and encrusted hardgrounds. Early cementation is represented mainly by homogeneous, bright orange luminescent, microcrystalline calcite and minor amounts of variably luminescent calcite spar. Early spar cements are commonly zoned while late cements are dull to non-luminescent. Borings consist mainly of *Trypanites weisei*, while encrusters are represented by *Spirorbis* sp., *Aulopora* sp. and rarely encrusting stromatoporoids. Hiatus concretions, commonly containing *Trypanites weisei* occur in close association with the hardgrounds.

XII. PHOTOGRAPHIC PLATES

PLATE 1

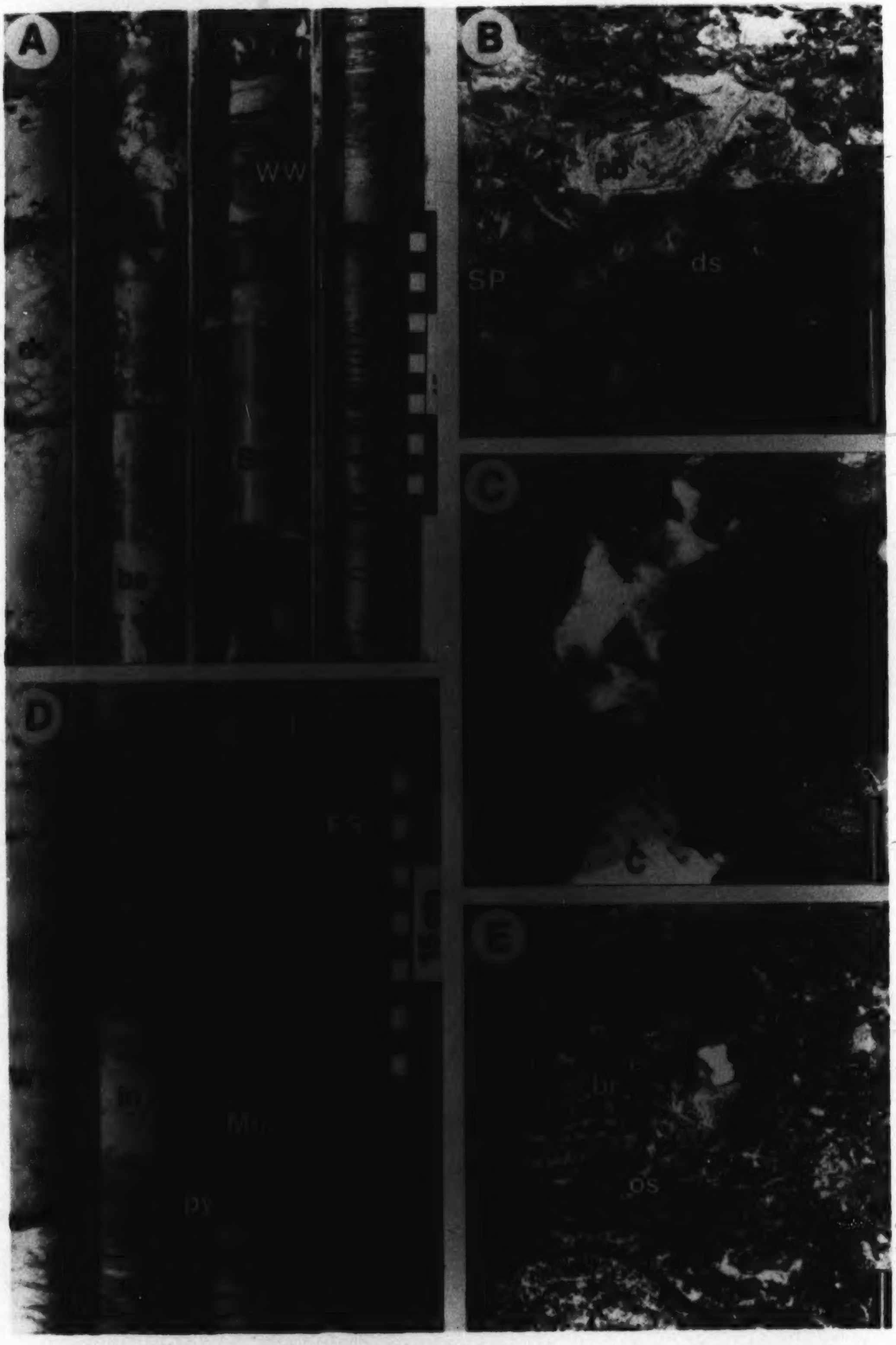
(A) Drill core showing sharp contact between dark coloured stromatoporoid floatstones of the Slave Point Formation (**SP**) and light grey, argillaceous packstone at the base of the Waterways Formation (**WW**). A hardground forms the contact (**arrow**) between the two formations. Note the abundance of small dendroid stromatoporoids (**ds**) and rare bulbous stromatoporoids (**bs**) in the Slave Point Formation. The Waterways Formation consists mainly of calcareous shale with thin beds of argillaceous limestone. Contact occurs at a depth of 224.0 m in HW-80-26. (Scale bar = 15 cm).

(B) Polished core showing hardground (**hg**) which forms the contact between the Slave Point (**SP**) and Waterways formations (**WW**). The hardground, which is developed at the top of dark brown cryptocrystalline, dendroid stromatoporoid (**ds**) floatstone, is sharply overlain by medium grey, argillaceous packstone. Post omission burrows (**pb**) occur in the Waterways Formation. Sample from depth of 224.4 m in HW-80-26. (Scale bar = 1 cm).

(C) Polished core of collapse breccia from the Slave Point Formation. Dark brown bituminous mudstones have been fractured and brecciated. Breccia is cemented by coarse sparry calcite (**c**). Sample from depth of 239.4 m in HW-79-3. (Scale bar = 1 cm).

(D) Core showing the shaley Upper Devonian strata which lie above the Slave Point Formation. The Waterways Formation (**WW**) consists of argillaceous limestone, grading upward into calcareous shale with limestone nodules (**ln**). The Waterways Formation is sharply overlain by bituminous shales of the Muskwa Formation (**Mu**). A thin band of pyrite (**py**) occurs at the contact. The Muskwa Formation is overlain by calcareous shale of the Fort Simpson Formation (**FS**). Core from depth of 422 to 425 m in HW-79-10. (Scale bar = 15 cm).

(E) Polished core of argillaceous, ostracod-brachiopod wackestone to packstone of the Waterways Formation. Note the lack of any physical sedimentaty structures due to the complete bioturbation of the sediment. Sample from depth of 416.9 m in HW-79-10. (Scale bar = 1 cm).


A
ds
bs
ww
B
po
SP
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c
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PLATE 2

(A) Polished core of intensely to completely bioturbated mudstone from the Waterways Formation. Bioturbation is represented by vague burrow outlines and colour contrasts between burrow fill and mudstone matrix. Sample from depth of 423.8 m in HW-79-9. (Scale bar = 1 cm).

(B) Polished core of siliceous, black bituminous shale that is typical of the Muskwa Formation. Note the abundance of small, white skeletal fragments which are the shells of *Styliolina* sp. Sample from depth of 412.2 m in HW-79-9. (Scale bar = 1 cm).

(C) Field photograph of section HR-99, showing shales and calcareous siltstone beds of member D of the Fort Simpson Formation (**FSd**). The boundary between member D (**dashed line**) and member C (**FSc**) is placed at the base of a 50 cm thick green grey calcareous siltstone unit. (Scale bar = 1 m).

(D) Field photograph of measured section HR-101 showing the calcareous shales with thin interbeds of variably quartzose limestone of member D of the Fort Simpson Formation. A well developed hardground (**hg**) occurs near the base of the section. (Scale bar = 1 m).

(E) Polished core of intensely bioturbated fossiliferous wackestone from the top of member A of the Fort Simpson Formation. Note the presence of three stacked, pyritized hardgrounds (**hg**). Sample from depth of 372.8 m in HW-79-9. (Scale bar = 1 cm).

(F) Polished core photograph of nodular, slightly fossiliferous mudstone from near the top of member A of the Fort Simpson Formation. Brachiopods (**br**) and gastropods (**gs**) are common. Light grey limestone nodules are fractured (**fr**), whereas darker, argillaceous mudstone matrix is not. Fractures are healed by cryptocrystalline or sparry calcite. Sample from depth of 246.8 m in HW-79-4. (Scale bar = 1 cm).

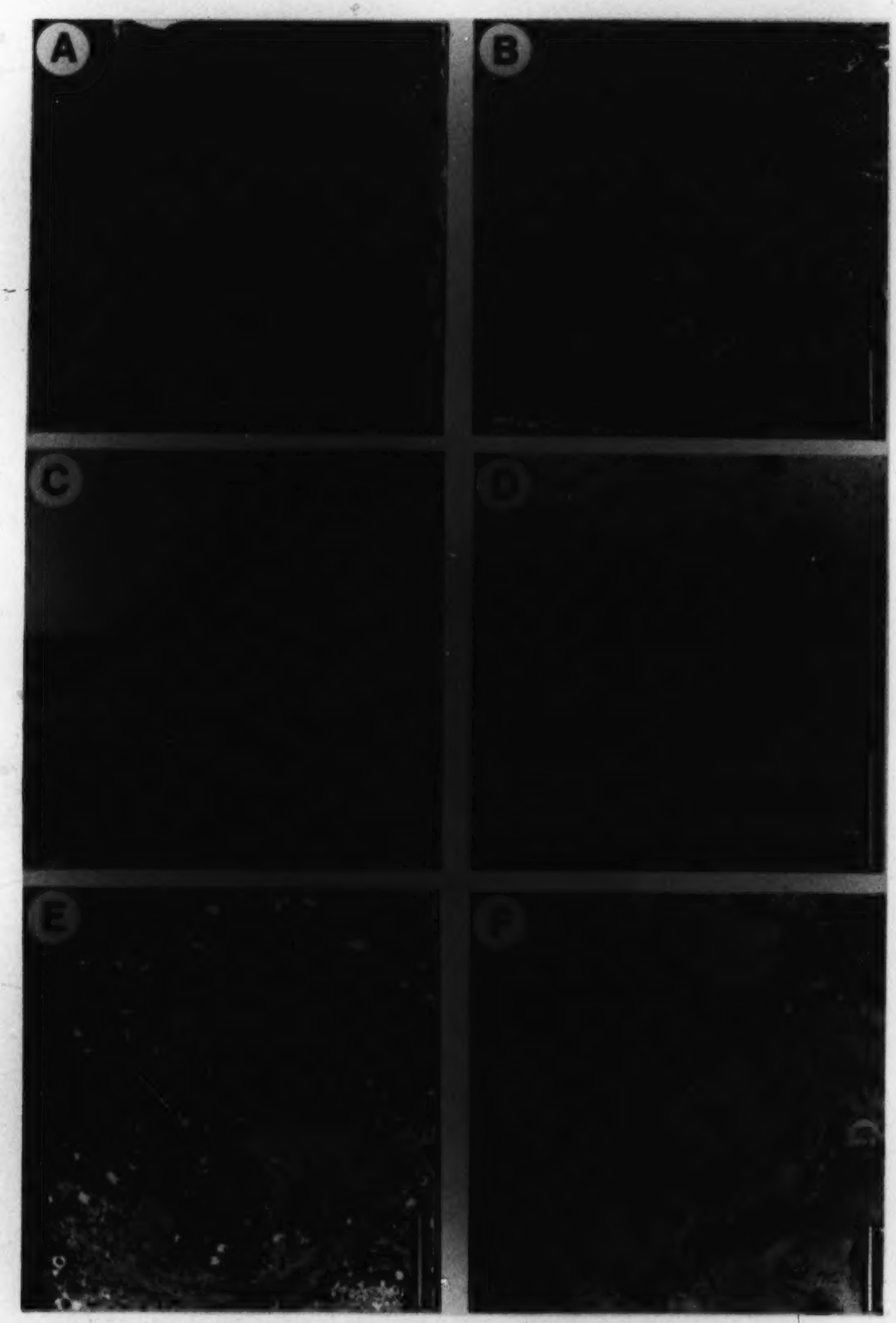

A
B
C
D
E
F

PLATE 3

(A) Core showing upper boundary (**arrow**) of Muskwa Formation (**Mu**). The dark bituminous shales of the Muskwa Formation (**Mu**), contain abundant *Styliolina* sp. (white specks), and shells of *Lingula* sp. and ostracodes. Locally, the Muskwa Formation contains thin interbeds and laminations of calcareous grey shale (**gs**). The Muskwa Formation is sharply overlain by grey calcareous shales of member A of the Fort Simpson Formation (**FSa**). Contact occurs at a depth of 308.4 m in HW-79-9. (Scale bar = 2.5 cm).

(B) Nodular limestone from the upper part of member A of the Fort Simpson Formation. The light grey, argillaceous mudstone nodules float in a darker, more argillaceous and recessive mudstone matrix. Sample from depth of 172 m in HW-79-1. (Scale bar = 2.5 cm).

(C) Typical shale lithology of member B of the Fort Simpson Formation. Note the presence of light grey, irregularly shaped limestone nodules in the dark calcareous shale. Sample from depth of 246.5 m in HW-79-7. (Scale bar = 2 cm).

(D) Typical mudrock which makes up part of member C of the Fort Simpson Formation. This unit consists of indurated, massive, unfossiliferous, calcareous mudrock. Core from between the depths of 118 and 123 m in HW-79-4. (Scale bar = 5 cm).

(E) Shale from near the base of member C of the Fort Simpson Formation, which consist of light to medium grey, laminated to fissile, calcareous shale with interbeds and interlaminations of dark grey to black, noncalcareous shale. Core from between the depths of 168.5 to 186 m. (Scale bar = 10 cm).

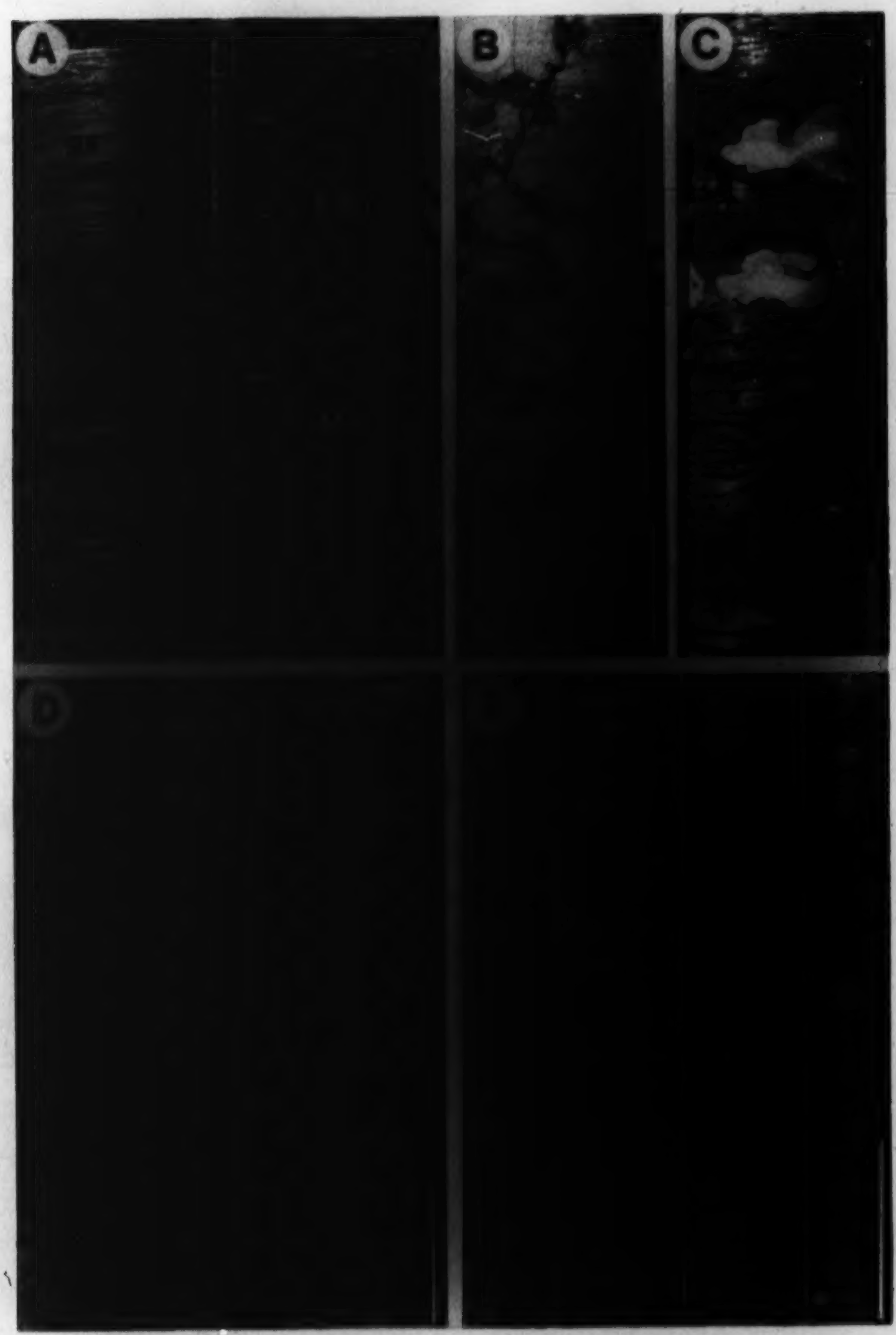

A
B
C
D

PLATE 4

(A) Light grey limestone nodule from calcareous shale of member A of the Fort Simpson Formation. The nodule represents early diagenetic cementation of a burrow fill, preserving the coiled shape of the burrow in full relief. Sample from depth of 176.9 m in HW-79-1. (Scale bar = 1 cm).

(B) Field photograph of the base of section HR-99 showing the contact (**arrow**) between very thinly interbedded calcareous, argillaceous, siltstone and silty shale of member C and the calcareous siltstone unit at the base of member D of the Fort Simpson Formation. (Scale bar = 30 cm).

(C) Photomicrograph of shelter structure beneath convex-up brachiopod valve (**br**). Note the columnar calcite cement (**co**) grading downward into blocky calcite cement (**bk**) which overlies dark peloids (**pe**). Sample from limestone bed in member D of the Fort Simpson Formation from 10.9 m above the base of section HR-99. Plane polarized light. (Scale bar = 100 µm or 0.1 mm).

(D) Photomicrograph of oncoid from limestone bed in member D of the Fort Simpson Formation. The oncoid is coated by dark, organic rich, cryptocrystalline calcite around a corroded brachiopod valve (**br**). Coatings are thickest around long dimension of shell and taper toward the end of the shell. Sample from 10 cm thick limestone bed at 13.8 m above the base of section HR-98. Plane polarized light. (Scale bar = 1µm or 0.1 mm).

(E) Intensely to completely bioturbated quartzose mudstone to calcareous siltstone in member D of the Fort Simpson Formation. Sample from near the upper part of the member at a depth of 139.7 m in HW-79-9. (Scale bar = 1 cm).

(F) Field photograph of *Rhizocorallium jenense* Zenker at the upper surface of the calcareous siltstone bed at the base of member D of the Fort Simpson Formation. Top of bed occurs at 1.5 m above the base of section HR-99. (Scale bar = 1 cm).

A
B
C
D
E

PLATE 5

(A) Polished hand sample showing storm deposited limestone bed. Note the basal shell lag, sharply overlain by laminated quartzose limestone which ispenetrated by *Diplocraterion parallelum* Torrell, *Planolites beverleyensis* Billings, *Cylindrichnus concentricus* Howard, *Skolithos linearis* Haldeman and *Palaeophycus tubularis* Hall. Sample from member D of the Fort Simpson Formation, 17.9 m above the base of section HR-100. (Scale bar = 1 cm).

(B) Field photograph of lower boundary of member A of the Escarpment Formation (**arrow**), at the base of ripple marked calcareous sandstone. The sandstone is overlain by rubbly weathering, argillaceous limestone. Boundary occurs 1.5 m above the base of section HR-103. (Scale bar = 10 cm).

(C) Polished core showing contact (**arrow**) between argillaceous siltstone of the Fort Simpson Formation and calcareous sandstone of the Escarpment Formation. Note the *Teichichnus* sp.at the contact which has caused a partial mixing of the two lithologies and the sparry calcite (**sc**) and dark calcareous siltstone (**st**) fills of *Planolites* sp. Sample from depth of 120.1 m in HW-79-9. (Scale bar = 1 cm).

(D) Field photograph showing the contact (**arrow**) between recessive shale at the top of member D of the Fort Simpson Formation and a rubbly weathering, resistant limestone unit at the base of the Escarpment Formation. Contact occurs 13.6 m above the base of section HR-102. (Scale bar = 1 m).

(E) Field photograph of resistant limestone unit at the base of member A of the Escarpment Formation. The dark resistant limestone lumps are surrounded by lighter, argillaceous limestone. The unit contains abundant brachiopods (**br**). From 15.4 m above base of section HR-101. (Scale bar = 2 cm).

(F) Polished core showing cross-laminated, calcareous siltstone- sandstone at the top of member E of the Escarpment Formation. The laminated appearance is the result of alternations of dark, quartz rich and light, calcite rich laminae. Note the truncated burrow (**arrow**). Sample from depth of 14.6 m in HW-79-9. (Scale bar = 1 cm).

A
B
C
D
E
F

PLATE 6

(A) Polished core showing light coloured nodular, quartzose limestone from near the base of the Alexandra Member of the Twin Falls Formation. Note the dark, irregular, "horse tail" seams (**hs**) around the margins of nodules. In some cases the seams are stylolitic (**sy**). Sample from depth of 10.5 m in HW-79-9. (Scale bar = 1 cm).

(B) Field photograph of the upper falls on Twin Falls Creek at section HR-108 showing the contact (**white arrow**) between calcareous sandstone-siltstone at the top of member E of the Escarpment Formation (**Ee**) and quartzose limestones at the base of the Alexandra Member (**Ax**). The basal part of the Alexandra Member consists of flaggy weathering, nodular limestones (**nl**) overlain by massive quartzose limestone (**ql**) and fossiliferous ("reefal") limestones (**fl**). (Scale bar = 1.5 m).

(C) Field photograph of section HR-104, showing outcrop pattern of member B of the Escarpment Formation (**Eb**). Member B consists of a basal, resistant quartzose unit (**ql**), a middle, recessive shale unit and an upper, resistant, fossiliferous limestone unit (**bs**). The upper limestone unit is biostromal. (Scale bar = 3 m).

(D) Field photograph showing sharp contact (**arrow**) between calcareous shales with siltstone lenses at the top of member A of the Escarpment Formation (**Ea**) and calcareous sandstone at the base of member B of the Escarpment Formation (**Eb**). Contact occurs 17.4 m above the base of section HR-105. (Pogo stick for scale is 92 cm long).

(E) Field photograph of shale in upper part of member A of the Escarpment Formation. Argillaceous limestone nodules (**ln**) occur in the blocky to fissile calcareous shale and are arranged in a crude bedded fashion. Photograph taken at 20 to 26 m above base of section HR-101. (Pogo stick for scale is 1.3 m long).

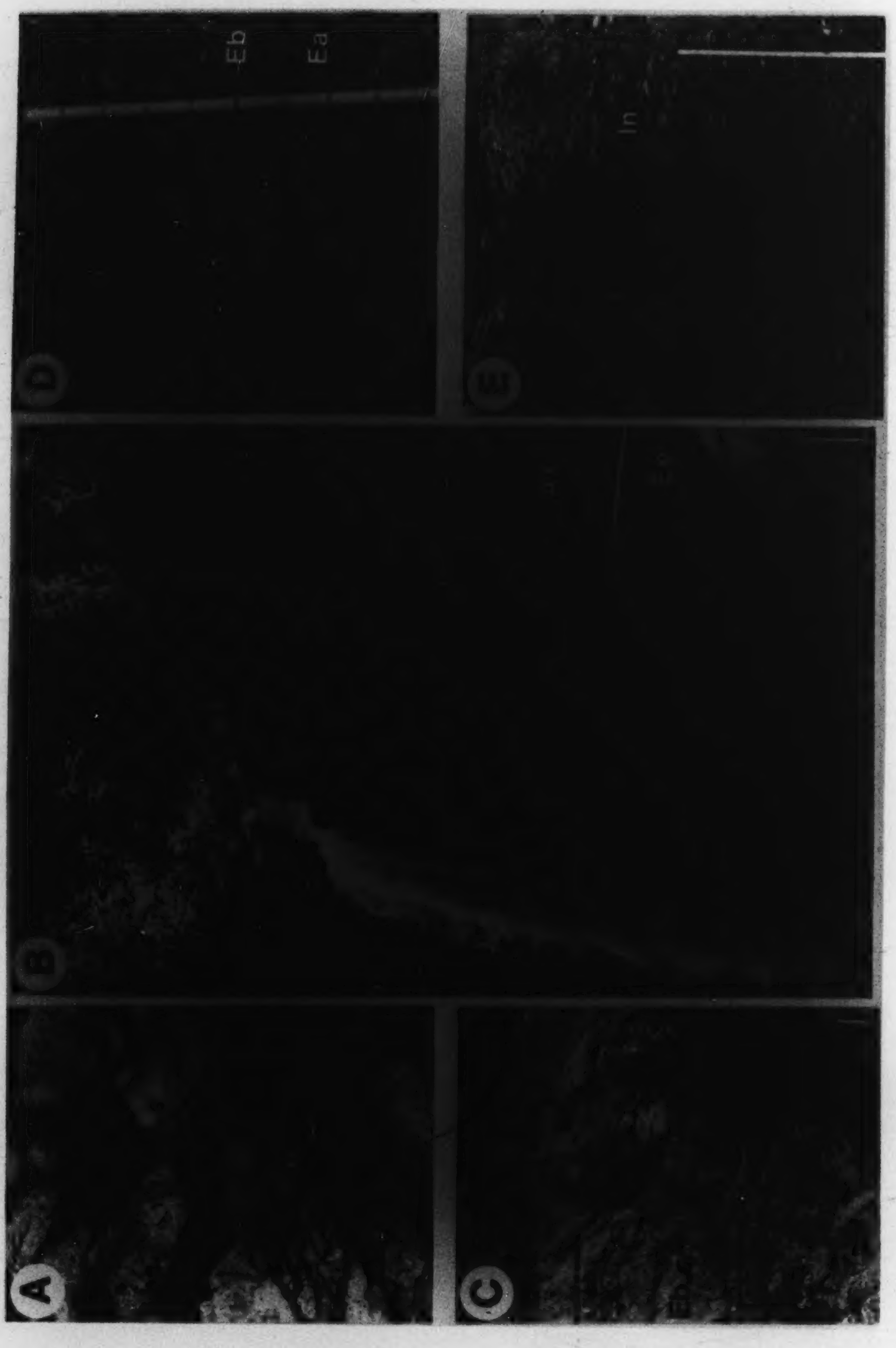

A
B
C
D
E
Eb
Ea
In

PLATE 7

(A) Hand sample showing traces of *Trichophycus* sp. (upper right hand corner) and *Palaeophycus striatus* Hall (lower part of photograph) developed in quartzose limestone from the base of the Escarpment Formation. Sample from rubble at the base of section HR-103. (Scale bar = 1 cm)

(B) Hand sample of *Diplocraterion* sp. developed on the upper surface of the rippled quartzose limestone bed at the base of the Escarpment Formation Sample from 6.2 m above the base of section HR-104. (Scale bar = 1 cm).

(C) Hand sample of branching network of *Planolites montanus* Richter (possibly *Chondrites* sp.von Sternberg) preserved on the upper surface of the quartzose limestone from the base of member A of the Escarpment Formation. Sample from rubble at the base of section HR-103. (Scale bar = 1 cm).

(D) Hand sample of quartzose limestone containing a high density of trace fossils. Note the presence of large branching *Thalassinoides* sp. (centre of photo), cylindrical traces of *Palaeophycus striatus* Hall (lower left), *Trichophycus* sp. (lower left, larger bulbous burrow) and small,cylindrical, tortuous *Planolites montanus* Richter (upper left). Sample from rubble at the base of section HR-103. (Scale bar = 1 cm).

(E) Field photograph of the resistant, fossiliferous, rubbly weathering limestone unit at the base of member A of the Escarpment Formation. Photo from the base of section HR-103. (Pogo stick for scale is 1.5 m long).

(F) Hand sample photograph of argillaceous, coral-brachiopod floatstone from the limestone unit (**see Plate 7E**) at the base of member A of the Escarpment Formation. Note the abundant solitary rugose corals (**rc**) and the branching network of *Thallasinoides* sp., which weather in relief due to the resistant nature of the burrow fills. Sample from rubble at the base of section HR-103. (Scale bar = 2 cm).

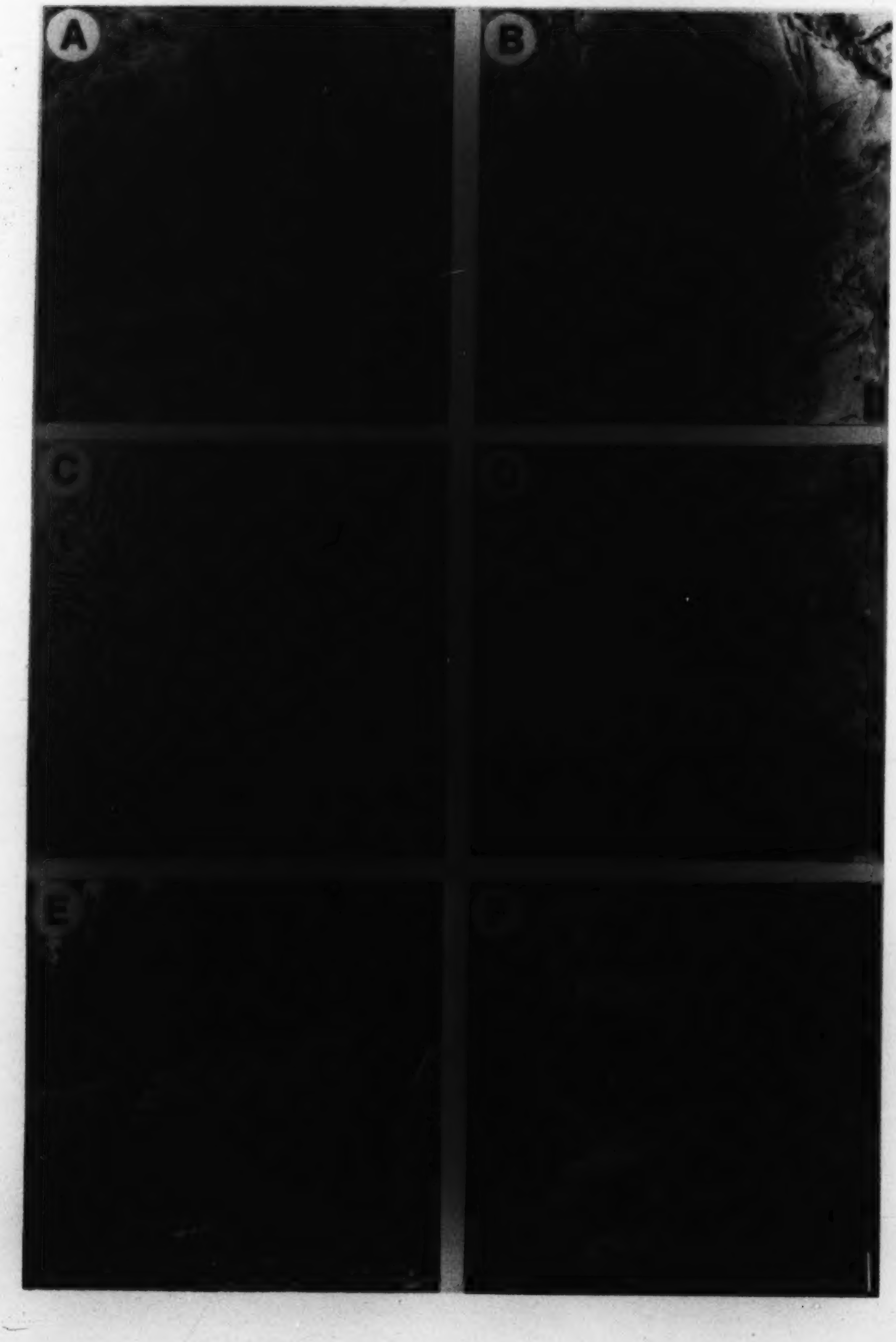

A
B
C
D
E
F

PLATE 8

(A) Polished core showing argillaceous, calcareous siltstone from the middle of member A of the Escarpment Formation. Intense bioturbation is represented by vague burrow outlines. Only remnants of original laminations are preserved in the rock. (Scale bar = 1 cm).

(B) Field photograph of section HR-111 showing the lower and middle limestone units, separated by recessive shale units, of member A of the Escarpment Formation (**Ea**). Note the contact (**dashed line**) between member D of the Fort Simpson Formation (**FSd**) and member A of the Escarpment Formation (**Ea**). (Scale bar = 3 m).

(C) Field photograph of upper limestone unit in member A of the Escarpment Formation at section HR-111. Note the rubbly weathered appearance of the limestone. (Pogo stick for scale is 1.5 m long).

(D) Field photograph of bedding plane from the limestone unit in Plate 8C. Note the abundance of cross cutting traces of possible*Cruziana* or *Rhizocorallium*. These traces enhance the rubbly bedded appearance of the limestone unit. (15 cm ruler for scale).

(E) Polished core showing brachiopod (**br**)-crinoid (**cr**) packstone from member A of the Escarpment Formation. Fine microcrystalline and sparry calcite cements are preserved in shelter structures (**ss**) beneath brachiopod valves. Sample from depth of 83.9 in HW-79-9. (Scale bar = 1 cm).

(F) Polished core showing black pebble floatstone in member A of the Escarpment Formation. Note the black, pyritized (**py**) rims around the pebbles and the presence of small borings (**bo**). Sample from depth of 75.1 m in HW-79-9. (Scale bar = 1 cm).

(G) Photomicrograph of ooid packstone from member A of the Escarpment Formation. Note the radial concentric (**rc**) texture of the calcite in the cortex and the thin concentric bands (**cb**) at the margin of the ooids. The ooids are cemented by fine blocky calcite spar. Sample from depth of 77.0 m in HW-79-9. Plane polarized light. (Scale bar = 100 μm).

A
B
C
D
E

PLATE 9

(A) Core showing argillaceous, fossiliferous limestone at the top of member B of the Escarpment Formation, overlain sharply (**arrow**) by calcareous, fissile shale at the base of member C of the Escarpment Formation. A pyritized hardground (**hg**) occurs near the top of member B. Contact occurs at a depth of 59.5 m in HW-79-9. (Scale bar = 5 cm).

(B) Field photograph of measured section HR-110 showing the outcrop pattern of the upper part of member A (**a**), member B (**b**) and the lower part of member C (**c**) of the Escarpment Formation. Only the upper limestone unit (**ul**) of member A is exposed at this locality. (Scale bar = 10 m).

(C) Field photograph of measured section HR-106 showing the outcrop pattern of members B (**b**), C (**c**) and D (**d**) of the Escarpment Formation. The contacts between members are shown by a dashed line. Note the massive cliff forming nature of the limestones of member D. The upper boundary of member D occurs at the top of a resistant, capping limestone unit (**arrow**). (Scale bar = 2 m).

(D) Field photograph of measured section HR-105 showing the outcrop pattern of members B (**b**), C (**c**) and D (**d**) of the Escarpment Formation. Note the thin limestone beds in the recessive shales of member C. (Scale bar = 5 m).

(E) Field photograph of measured section HR-107 showing the outcrop pattern of the upper part of member B (**b**), member C (**c**) and member D (**d**) of the Escarpment Formation. Distinctly bedded limestones at the base of member D are overlain by a more massive biostromal unit (**bs**), the contacts of which are indicated by black arrows. The biostromal unit is overlain by a resistant, ledge forming limestone (**white arrow**). The top of the capping unit is the upper boundary of member D. (Scale bar = 5 m).

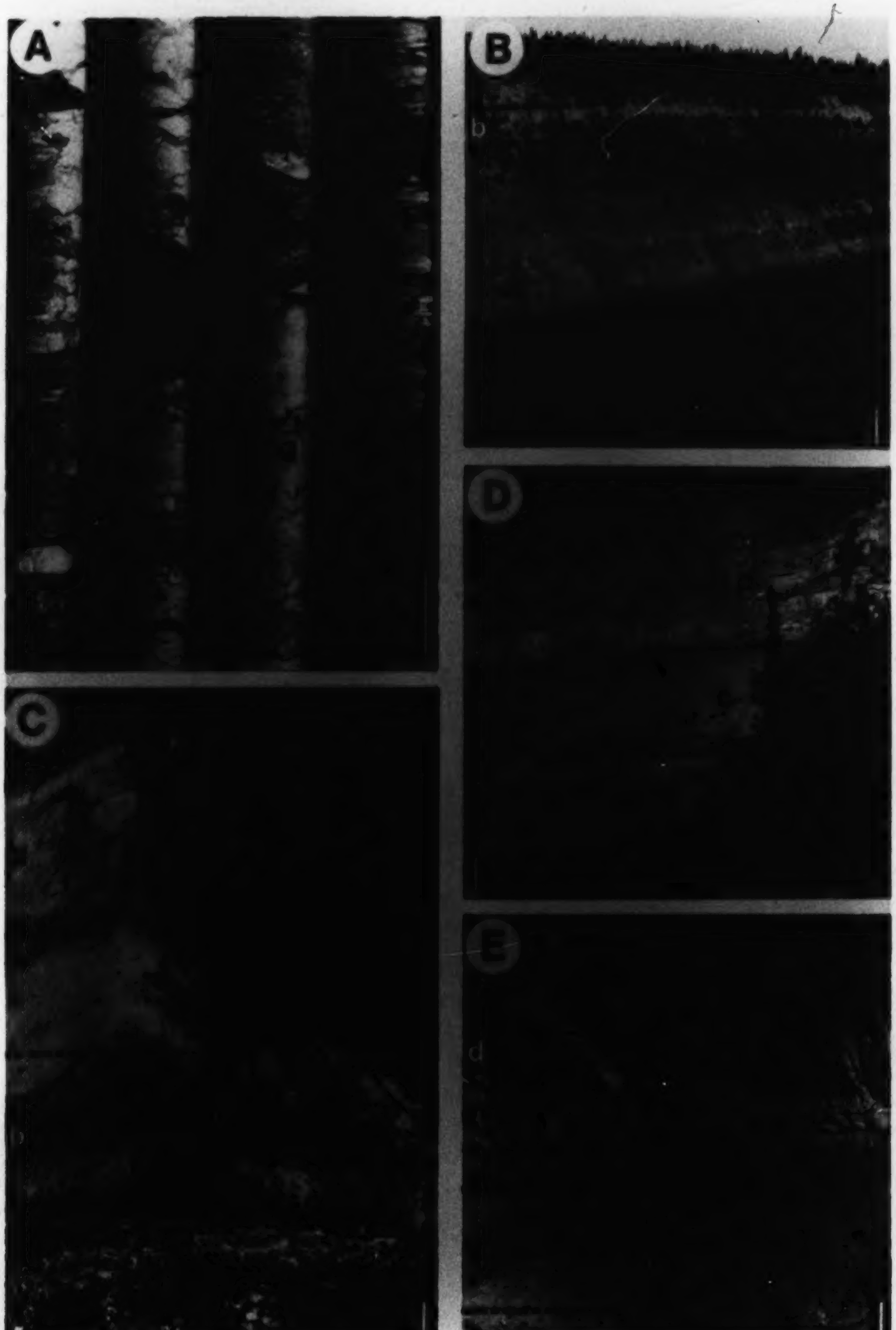

A
B
b
C
D
E
d

PLATE 10

(A) Field photograph of calcareous sandstone at the base of member B of the Escarpment Formation. The unit shows evidence of truncated bedding (**tr**), scour (**sc**) and vertical escape traces represented by *Skolithos linearis* Haldeman (**es**). Many of the burrows are truncated by overlying beds. From 5.5 m above the base of section HR-106. (Scale bar = 5 cm).

(B) Photomicrograph of calcareous sandstone at the base of member B of the Escarpment Formation. Note the abundance of quartz grains (**q**), calcite (**c**), and some muscovite laths (**m**). Cross polarized light. Sample from 5.7 m above the base of section HR-106. (Scale bar = 100 µm)).

(C) Polished core of crinoidal packstone from the base of the limestone unit at the top of member B of the Escarpment Formation. Crinoid ossicles (**cr**), blackened skeletal fragments (**bs**) and black rimmed limestone pebbles (**lp**) are abundant in the the crudely bedded packstone. Sample from 9.9 m above the base of section HR-107. (Scale bar = 1 cm).

(D) Polished hand sample showing coral-stomatoporoid bindstone from the top of member B of the Escarpment Formation. Note the low domal *Alveolites* sp. (**Av**) and encrusting stromatoporoids (**st**). The matrix consists of mudstone to wackestone. Burrows (**bu**) are commonly dolomite filled. Sample from 39.3 m above the base of section HR-110. (Scale bar = 1 cm).

(E) Polished core showing bioturbated wackestone from the top of member B of the Escarpment Formation. Note the contrast in colour and fineness of burrow fills (**bf**) compared to the more argillaceous wackestone matrix (**wm**). Fine skeletal material outlines burrow spreiten (**bs**). Black rimmed pebble (**bp**) occur locally. Sample from depth of 62.3 m in HW-79-9. (Scale bar = 1 cm).

(F) Core showing limestone nodules in calcareous shales of member C of the Escarpment Formation. Note the presence of calcite spar filled fractures (**sf**) and a rugose coral (**rc**) in the nodules. Core from between 46 to 49 m in HW -79-10. (Scale bar = 2.5 cm).

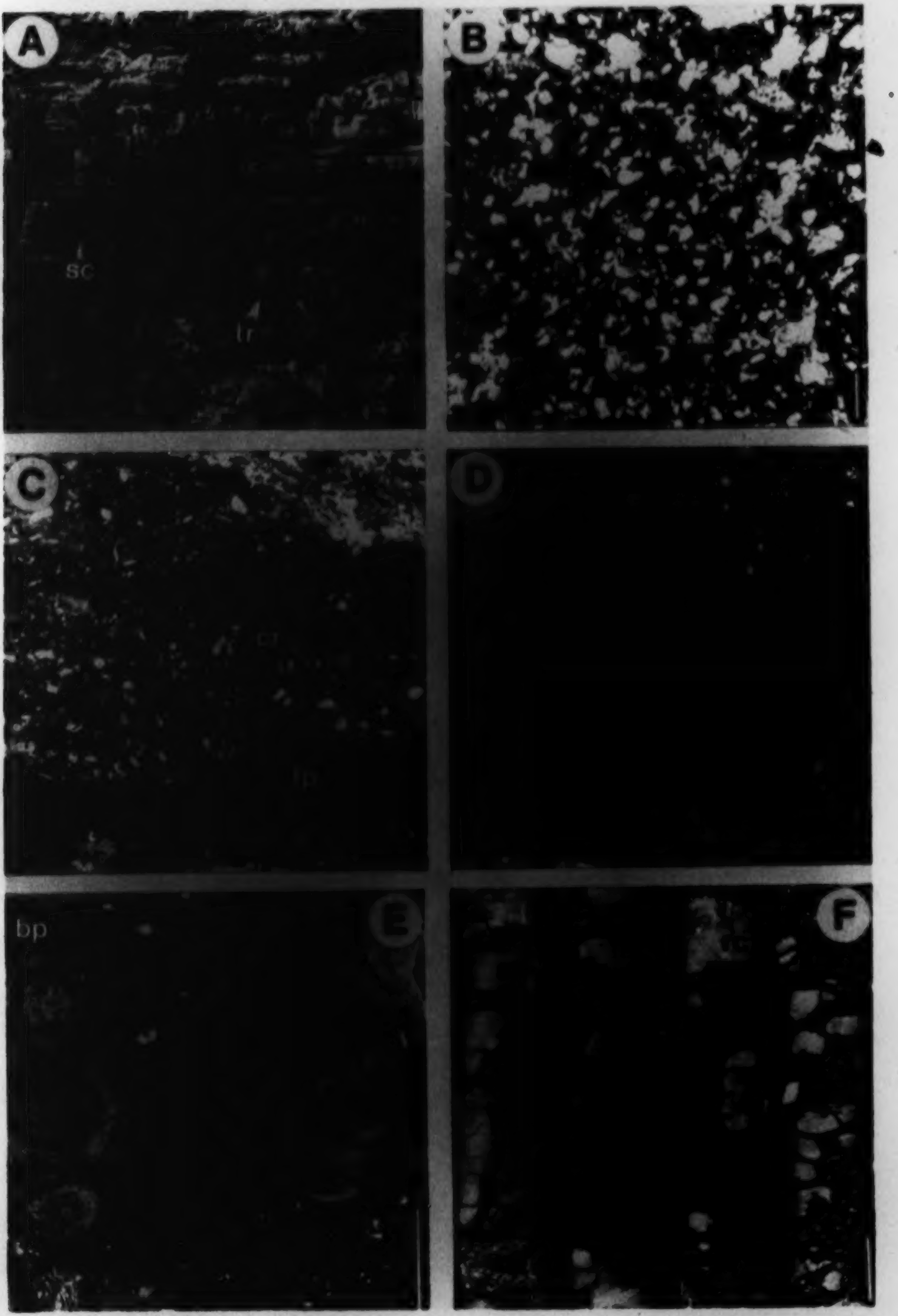

A
sc
tr
B
C
cr
lp
D
bp
E
F

PLATE 11

(A) Field photograph of the lower falls on Twin Falls Creek at section HR-108. The falls are formed by the resistant limestones of member D of the Escarpment Formation. Note the contact (**dashed line**) between recessive shaley strata of the top of member C (**c**) and the more resistant argillacous limestones at the base of member D (**d**) of the Escarpment Formation. A thin biostromal limestone unit occurs near the top of member D (**between the white arrows**). A resistant capping limestone unit (**white arrow**) at the top of the falls forms the upper boundary of member D. (Scale bar = 2 m).

(B) Field photograph of limestone unit from near the middle of member C of the Escarpment Formation, at the top of section HR-104. Massive quartzose limestone (**ql**) forms the base of the unit. It is overlain by fossiliferous grainstones (**fg**) which grade upward into rubbly weathering, fossiliferous floatstones (**ff**). The rubbly unit is sharply overlain by a coral-stromatoporoid bindstone (**cs**). (Pogo stick for scale is 1.5 m long).

(C) Polished core showing intensely to completely bioturbated wackestone from the upper part of member C of the Escarpment Formation. Vague burrows (**bu**) are commonly highlighted by concentrations of shell material. Black rimmed limestone pebbles (**lp**) containing *Trypanites* sp. (**Tr**) are common. Sample from depth of 49.8 m in HW-79-9. (Scale bar = 1 cm).

(D) Polished hand sample showing crinoidal packstone from limestone bed (**ff** in Plate 11 B) near middle of member C of the Escarpment Formation. White crinoid ossicles and some brachiopod valves (**br**) and *Thamnopora* sp. (**Th**) fragments, are abundant. (Scale bar = 1 cm).

(E) Field photograph showing the massive cliff forming nature of the limestones comprising member D of the Escarpment Formation, at section HR-105. The contact between recessive shales of member C and the thinly bedded limestones of member D occurs at the base of the cliff section. Cliff face is approximately 22 metres high.

A
B
C
D
E

PLATE 12

(A) Field photograph of section HR-109 at Louise Falls showing the outcrop pattern of member D of the Escarpment Formation. Note the distinctive thin bedded appearance of the massive limestones at the base of member D. A thin biostromal limestone unit (**bl**) occurs at the top of the thin bedded limestones (**white arrow**). The biostromal unit is overlain by a recessive, rubbly weathering, argillaceous limestone unit (**al**), with thin shaley interbeds. A resistant capping limestone unit (**cl**) forms the top of Louise Falls. The top of this bed represents the upper boundary of member D. (Field assistant for scale).

(B) Field photograph showing contacts between members D (**Ed**) and E (**Ee**) of the Escarpment Formation, and massive cliff forming limestones of the Alexandra Member (**Ax**) of the Twin Falls Formation (**dashed black lines**). Note the argillaceous nature of the upper part of member D and the resistant nature of the capping limestone unit at the top of the member. The recessive covered interval above member D represents the shales of member E of the Escapment Formation. The contact between the Escarpment and Twin Falls formations is covered at this locality. Section occurs on southeast bank of Hay River opposite section HR-109 at Louise Falls. (Scale bar = 5 m).

(C) Field photograph of thin, parallel bedded argillaceous limestones of member D at the base of the lower falls on Twin Falls Creek. Thin shaley seams (ss) occur between the limestone beds. (Scale bar = 20 cm).

(D) Field photograph of thin, wavy, parallel bedded argillaceous limestone at the base of member D of the Escarpment Formation. Note the recessive shaley seams (ss) between limestone beds. Beds occur 42.5 m above the base of section HR-105. (Scale bar = 20 cm).

A
d
a
b
B
C
D

PLATE 13

(A) Polished core showing typical argillaceous limestone of member D of the Escarpment Formation. Note the presence of light coloured mudstone surrounded by darker argillaceous wisps. The nodular appearance of the rock is enhanced by the presence of vague burrows (**bu**). Note the spar filled cracks (**sf**) in the nodules. Sample from a depth of 42.5 m in HW-79-9. (Scale bar = 1 cm).

(B) Polished hand sample photograph of dark brown, bioturbated mudstone from member D of the Escarpment Formation. *Teichichnus* sp. (**Te**) and *Chondrites* sp. (**Ch**) occur in the mudstone. Sample from 15 m above the base of section HR-108. (Scale bar = 1 cm).

(C) Polished hand sample of coral-stromatoporoid bindstone from the biostromal unit near the top of member D of the Escarpment Formation. Tabular stromatoporoids (**es**), irregularly shaped *Alveolites* sp. (**Al**) and *Thamnopora* sp. (**Th**) fragments are abundant. Thin lenses of dark coloured, dolomitic, limestone (**cl**) occur in the bindstone. Sample from 22.6 m above the base of section HR-108. (Scale bar = 1 cm).

(D) Field photograph of the biostromal unit near the top of Member D of the Escarpment Formation, at Louise Falls. Note the domal *Alveolites* sp. (**Al**) and the flat encrusting stromatoporoids (**Es**). Lenses of argillaceous wackestone to floatstone (**af**) occur throughout the unit. Unit occurs 9.7 m above the base of section HR-109. (Scale bar = 10 cm).

(E) Polished hand sample of coral-brachiopod floatstone from the biostromal unit near the top of Louise Falls (see Plate 13D). Note the presence of mud filled brachiopods (**br**), rugose corals (**rc**), and small patches of sparry calcite (**c**). (Scale bar = 1 cm).

(F) Field photograph of recessive rubbly weathering, thinly bedded limestone near the top of member D of the Escarpment Formation at Louise Falls. The recessive unit grades upward into more resistant limestones at the top of member D. The biostromal limestone unit (**bu**) seen in Plate 13D, forms the lowest bench at the middle of Louise Falls. (Field assistant for scale).

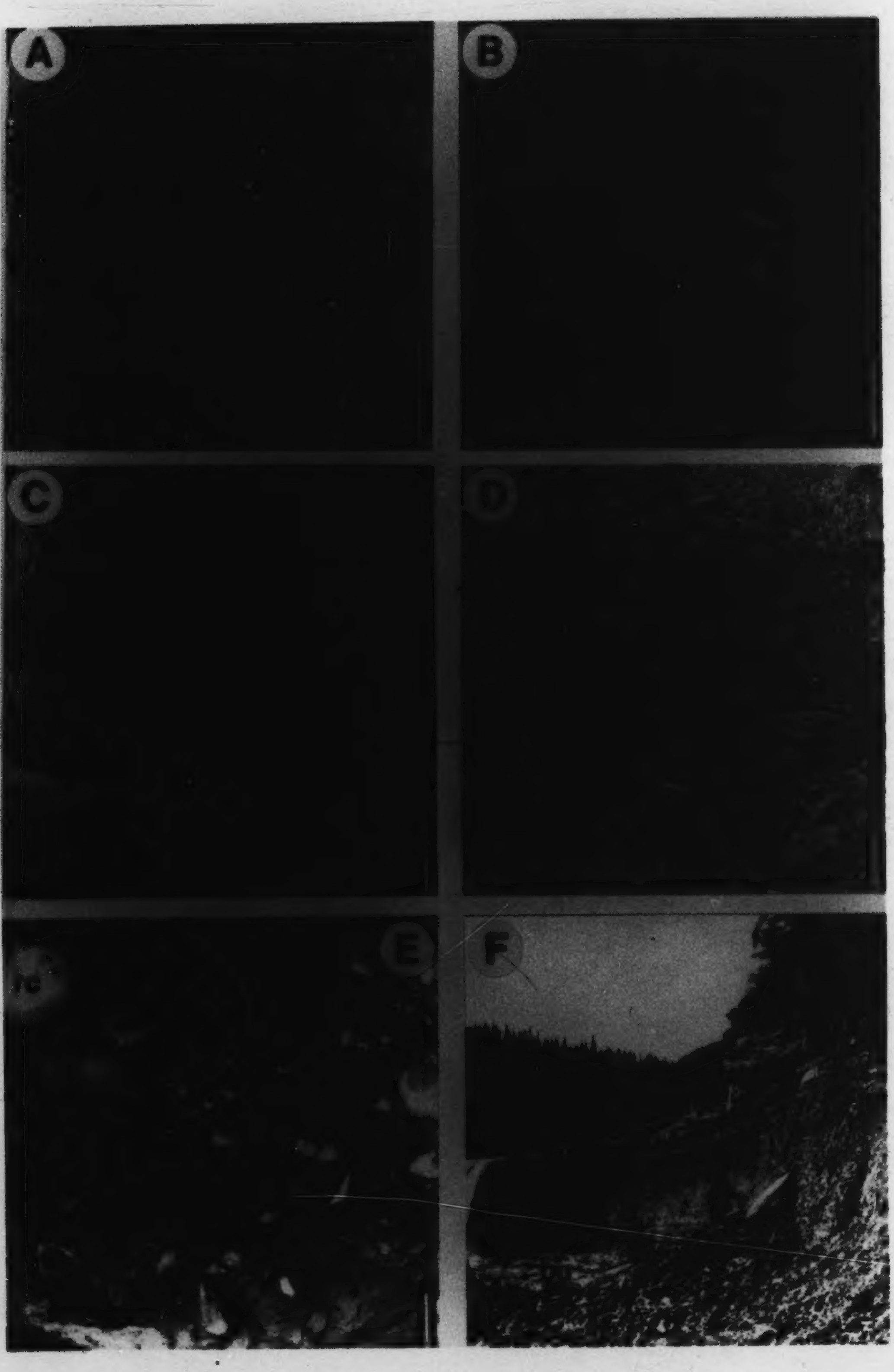

A
B
C
D
rc
E
F

PLATE 14

(A) Bedding plane showing coral-brachiopod floatstone at the top of member D of the Escarpment Formation. Note the abundance of rugose corals (**rc**). The mudstone matrix is intensely bioturbated with cylindrical, gently curved burrows (**bu**) preserved locally. Photograph from top of the resistant capping unit at the top of Louise Falls at 17 m above the base of section HR-109. (Scale bar = 5 cm).

(B) Drill core showing part of member E of the Escarpment Formation. A transitional unit (**tr**), consisting of calcareous shale with thin interbeds and lenses of calcareous sandstone is overlain (**arrow**) by massive, laminated, calcareous sandstone to siltstone (**ss**), with some thin shaley stringers. (Scale bar = 5 cm).

(C) Photomicrograph of calcareous sandstone to siltstone from the upper part of member E of the Escarpment Formation. Linear concentrations of calcite (**cc**) and abundance of detrital quartz (**q**) give the rock its characteristic laminated appearance. Sample form 36.5 m above the base of section HR-108. Cross polarized light. (Scale bar = 100 µm or 0.1 mm).

(D) Photomicrograph of quartzose limestone from member E of the Escarpment Formation. Note that most of the sample consists of calcite (**cc**) , abundant dark, microcrystalline peloids (**p**) and lesser amounts of quartz (**q**). Sample from depth of 28.5 m in HW-79-10. Cross polarized light. (Scale bar = 100 µm or 0.1 mm).

(E) Polished core showing calcareous sandstone to siltstone from member E of the Escarpment Formation. Thin intercalations of light coloured calcareous sandstone and the darker, argillaceous sandstone enhance the thinly bedded appearance of the rock. This unit is penetrated by deformed, vertical *Skolithos* sp., *Chondrites* sp. (**Ch**) and small deformed, light coloured *Planolites* sp. Note that the burrows are truncated by an overlying unit of cross-laminated calcareous sandstone. Sample from a depth of 16.2 m in HW-79-9. (Scale bar = 2 cm).

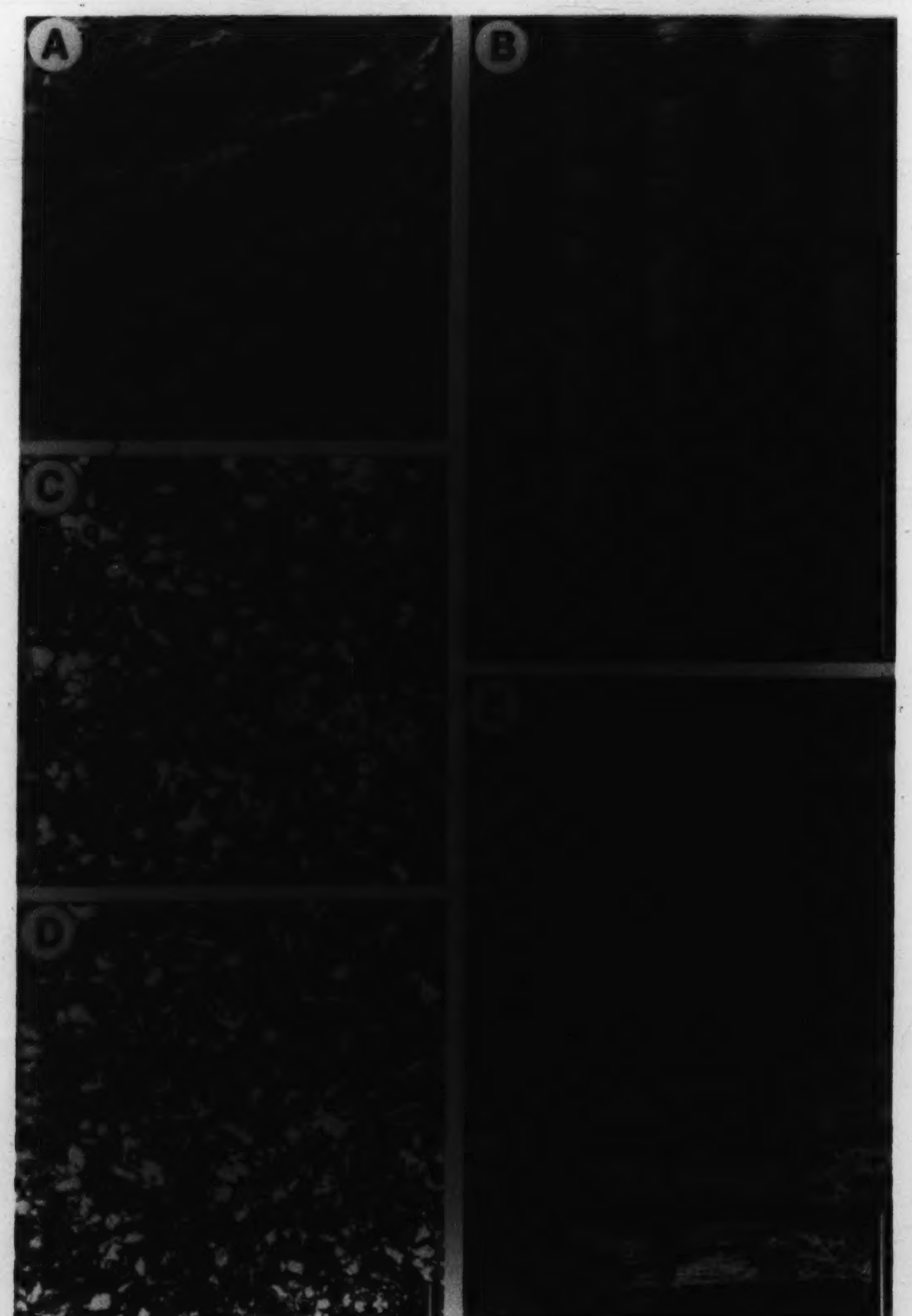

A
B
C
D

PLATE 15

(A) Hand sample showing calcareous sandstone from member E of the Escarpment Formation. *Diplocraterion* sp. (centre of photo) and *Uchirites* sp. (fine scratch marks) are preserved on the upper surface of the bed. Sample from rubble at the base of member E of the Escarpment Formation at Louise Falls. (Scale bar = 1 cm).

(B) Hand sample showing *Scolicia* sp. in calcareous sandstone from member E of the Escarpment Formation. Sample from 36.5 m above the base of section HR-109 at Twin Falls Creek. (Scale bar = 1 cm).

(C) Polished core showing medium brown stromatoporoid bindstone from the Alexandra Member of the Twin Falls Formation. Note that the light coloured, tabular stromatoporoids are separated by darker, stylolitic, dolomitic mudstone matrix. Sample from depth of 7.9 m in HW-79-9. (Scale bar = 1 cm).

(D) Polished core showing medium brown stromatoporoid floatstone from the Alexandra Member of the Twin Falls Formation. Small, light coloured dendroid stromatoporoid fragments float in a dark, stylolitic (**st**) dolomitic mudstone matrix. Thin calcite rims surround geopetally filled gastropod (**gs**) and clumps of dendroid stromatoporoids. Sample from depth of 6.1 m in HW-79-9. (Scale bar = 1 cm).

(E) Field photograph of Alexandra Falls on Hay River, showing the type section of the Alexandra Member of the Twin Falls Formation. Note the contact (**arrows**) between the calcareous sandstone at the top of the Escarpment Formation and even bedded, cliff forming limestones of the overlying Alexandra Member. The cliff section is approximately 25 m high.

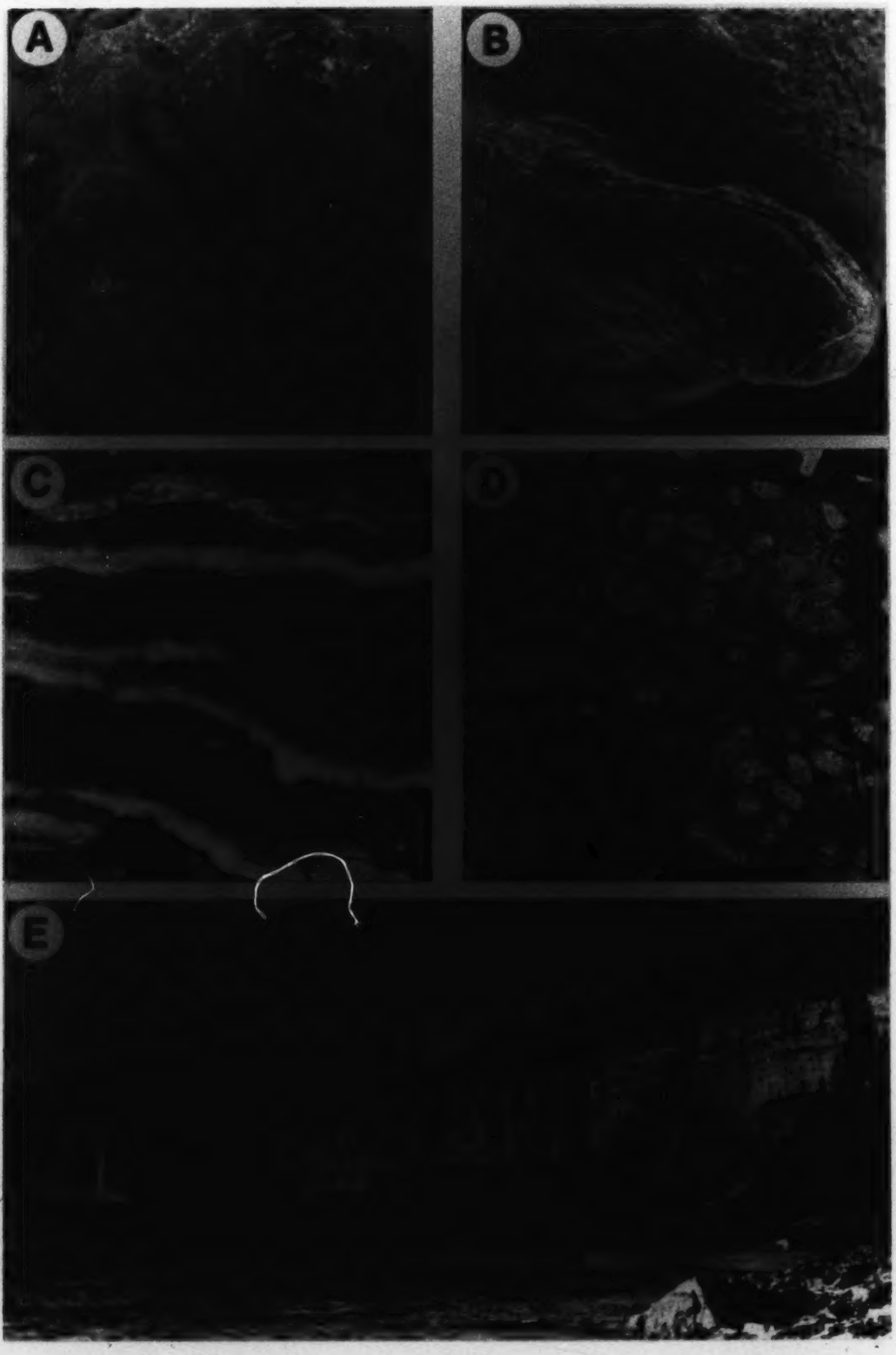

A
B
C
D
E

PLATE 16

(A) Polished core showing type I hardground (**h**) from the upper boundary of the Slave Point Formation. Relatively sharp walled, branching, omission burrow (**o**) is filled by light coloured wackestone which contains post omission burrows (**p**). The omission burrow fill contains black rimmed pebbles (**arrow**). Note the irregular topography of the upper surface of the hardground where the omission burrow fill has been partially eroded. A thin rim of pyrite occurs at the surface of the hardground (**h**). Sample from depth of 315.5 m in HW-79-7. (Scale bar = 1 cm).

(B) Polished core showing type I hardground, from the top of member A of the Fort Simpson Formation, consisting of three mineralized hardgrounds (**1, 2, 3**). The wackestone matrix below the lowest hardground surface (**1**), has a mottled appearance due to the effects of intense bioturbation by pre-omission burrowers. A brachiopod in the matrix (**arrow**) is filled by micrite and early calcite spar cements. Sample from depth of 372.8 m in HW-79-9. (Scale bar = 1 cm).

(C) Polished core showing type I hardground from the limestone bed at the top of member B of the Escarpment Formation. At least 5 pyritized surfaces (**small white arrows**) drape a large dark rimmed hiatus concretion (**hc**) The wackestone matrix is intensely bioturbated. Sample from depth of 75.0 m in HW-79-10. (Scale bar = 1 cm).

C
B
A

PLATE 17

(A) Negative print from thin section of a type II hardground from the upper part of member D of the Fort Simpson Formation. Note the sharp upper surface of the hardground (**h**) with truncated stromatoporoids and *Trypanites weisei* which cross cut both allochems and matrix. Pyrite (**py**) is preferentially concentrated in the micrite fill of the borings. The borings contain dark coloured micrite with some fossil fragments. In some cases, the borings are filled by calcite spar and fossil fragments (**s**). The spar filled borings penetrate an omission burrow (**o**). The contact between the spar cement and the overlying micrite in the borings corresponds to the outer margin of the burrow (**o**). More than one generation of *Trypanites weisei* is present as indicated by the cross cutting relations (**cr**) and differing fills of some borings and the fractures (**F**) in the hardground which cross cut some borings and are in turn cut by borings (**s**). The vague outlines of pre-omission (**p**) burrows are evident by the concentration, locally, of skeletal material. Note the presence of calcite microsparspar cements geopetally overlying pelloidal micrite in small borings in the centres of dendroid stromatoporoids. The geopetal fills are oriented at different angles in different stromatoporoids. Sample from a depth of 210.5 m in HW-79-6. (Scale bar = 5 mm).

PLATE 18

(A) Polished core showing a type II hardground from the upper boundary of the Slave Point Formation. The planar surface of the hardground sharply truncates dendroid stromatoporoids. The upper surface is penetrated by *Trypanites weisei* **(T)**. Note the post omission burrows (o) in the wackestone of the Waterways Formation above the hardground. Sample from a depth of 224.3 m in HW-80-26. (Scale bar = 5 mm).

(B) Hand sample showing a type III hardground from the upper part of member D of the Fort Simpson Formation. Truncated brachiopods at the hardground surface are represented by valve outlines. The surface is encrusted by *Spirorbis* sp. **(S)** and *Aulopora* sp. **(A)**, which are only partially preserved due to the effects of modern erosion. Note the fine pitted nature of the upper surface of the hardground, possibly indicating solution as a result of subaerial exposure. Sample from 1.1 m above the base of measured section HR-101. (Scale bar = 1 cm).

PLATE 19

(A) Hand sample of a type II hardground from the upper part of member D of the Fort Simpson Formation. The hardground (**hg**) is dificult to distinguish from the large hiatus concretion (**hc**). The hardground surface contains sharply truncated brachiopods (**br**), and sharp walled circular openings (**so**) of possible biogenic origin. The hiatus concretion contains shallow linear depressions which may represent the eroded burrows and small circular borings of the ichnogenus *Trypanites*. Coarse, abraded skeletal material fills the area between the concretion and the hardground. Sample from 1.1 m above the base of section HR-101. (Scale bar = 1 cm).

(B) Hand sample of a type III hardground from the upper part of member D of the Fort Simpson Formation. Note the density of encrusting *Spirorbis* sp. (**S**) and the solitary *Aulopora* sp. (**A**) on the upper surface of the hardground. The upper surface has microrelief consisting of smooth sided, shallow pits (**p**) which do not appear to be of biogenic origin. These may be microkarst features indicative of a period of subaerial exposure. Sample from 1.1 m above the base of measured section HR-101. (Scale bar = 1 cm).

A
hg
B

PLATE 20

(A) Photomicrograph of the upper surface of type II hardground from the Slave Point Formation. Possible microborings (**arrow**) penetrate the upper surface of the hardground. Finely crystalline pyrite, is concentrated at the upper surface and becomes more diffuse downward. Sample from depth of 93.7 m in JMBS-11. The hardground occurs 2.4 m below the upper boundary of the Slave Point Formation. Plane polarized light. (Scale bar = 100 μm).

(B) Photomicrograph of the upper surface of a type I hardground from the upper limestone bed in member A of the Fort Simpson Formation. Note the stylolitic (**arrow**) surface of the hardground. Sample from depth of 162 m in HW-79-6. Plane polarized light. (Scale bar = 100 μm).

(C) Photomicrograph of *Trypanites weisei* from the type II hardground in Plate 17. The sharp walled boring (**arrows**) has truncated a crinoid ossicle. Small opaque pyrite crystals occur in the boring fill. Plane polarized light. (Scale bar = 250 μm).

(D) Photomicrograph of *Trypanites weisei* from the type II hardground in Plate 17. Note the sharp walls of at least two generations of borings (1, 2). The borings truncate skeletal material (arrow-upper left) and matrix. Plane polarized light. (Scale bar = 100 μm).

(E) Photomicrograph of *Trypanites weisei* from the type II hardground in Plate 17. The contact between the boring wall and the matrix of the hardground (**arrow**) is sharp. The boring is filled by dark microcrystalline peloids (**p**) cemented by calcite microspar (**m**). Plane polarized light. (Scale bar = 100 μm).

(F) Photomicrograph of *Typanites weisei* from the type II hardground in Plate 17. Note that the sharp walled boring (**arrow**) contains a fill of dark microcrystalline calcite, possibly representing clumps of peloids (**p**), cemented by calcite microspar (**m**). The peloids appear to have been biogenically altered. A crinoid ossicle is penetrated by small borings (**b**). PLane polarized light. (Scale bar = 100 μm).

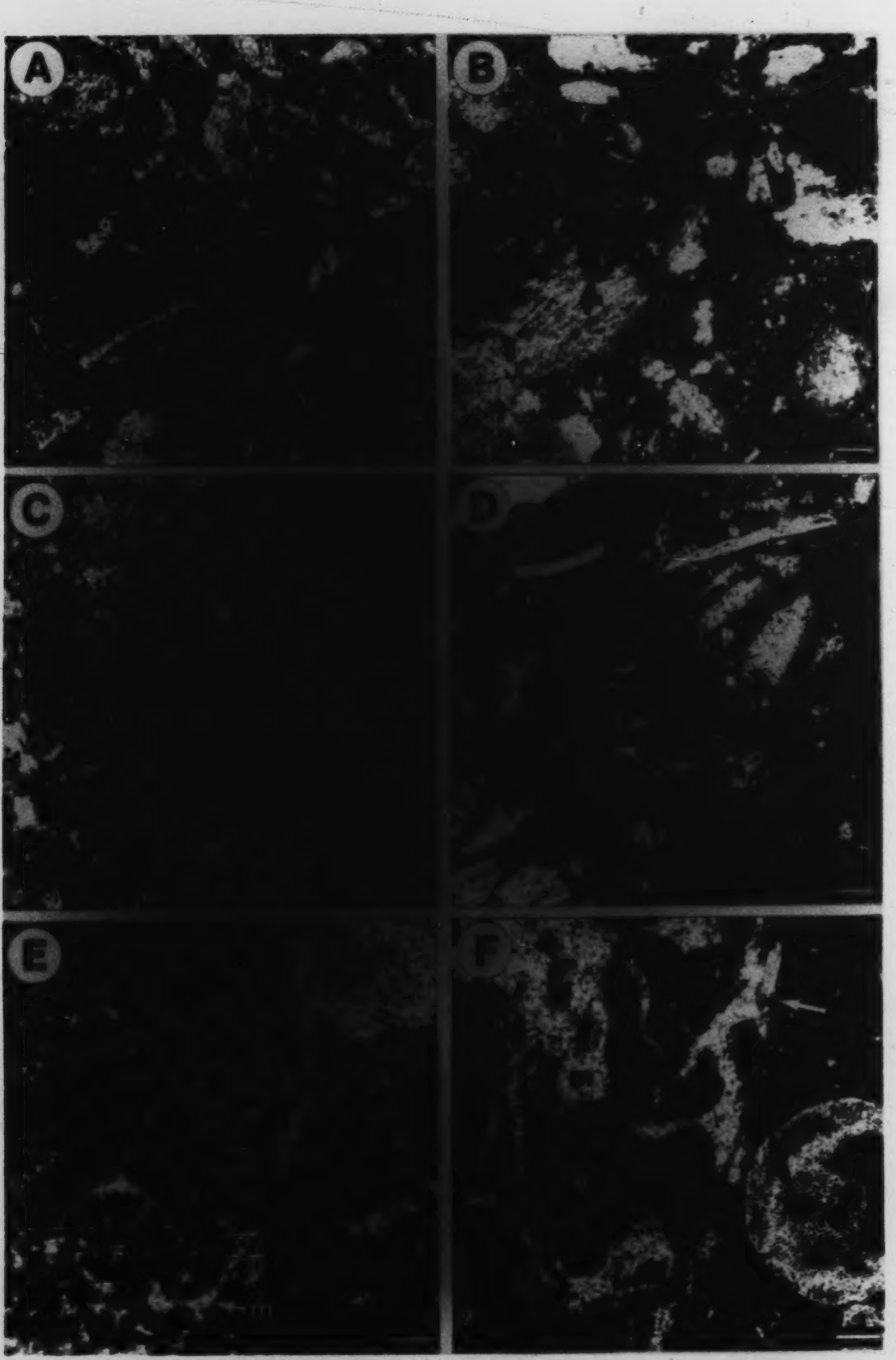

A
B
C
D
E
m
F

PLATE 21

(A) Photomicrograph of the fill of *Trypanites weisei* from the type II hardground in Plate 17. Note that the sharp walled boring (**arrow-top centre**) is filled by blocky sparry calcite cement (**c**), sharply overlain by dark microcrystalline calcite (m). Large opaque crystal of pyrite (**p**) occur at the contact. The contact occurs at the outer margin (see Plate 17) of a burrow (**arrow-centre right**) marked by the prescene of small pyrite crystals. Plane polarized light. (Scale bar = 100 μm).

(B) Photomicrograph of *Spirobis* sp. which encrusts a stromatoporoid (**arrow**). The walls of the serpulid tube consist of finely crystalline calcite (**arrow**). A geopetal fill in the coiled tube, consists of microcrystalline calcite (**m**) overlain by calcite spar cement (**c**). Sample from depth of 211.2 m in HW-79-1. Plane polarized light. (Scale bar = 100 μm).

(C) Polished slab showing a type III hardground from the upper part of member D of the Fort Simpson Formation. Note the presence of sharp walled, circular openings (**white arrow**) at the hardground surface which taper downward into irregularly shaped tubes filled by quartzose limestone. Dark dolomite and pyrite are concentrated in the material surrounding the tubes (**black arrow**). Sample from 1.1 m above the base of section HR-101. Slab cut from hardground in Plate 19A. (Scale bar = 5 mm).

(D) Photograph of encrusted pedicle valve of brachiopod from the limestone bed at the base of member A of the Escarpment Formation. The valve is densely encrusted by *Aulopora* sp. (**A**), with a lone occurence of *Spirorbis* sp. (**S**). Sample from 2.0 m above the base of section HR-103. (Scale bar = 5 mm).

(E) Photomicrograph of truncated brachiopod valve (**arrow**) at the surface of a type I hardground from the Slave Point Formation. Note the presence of euhedral cubes of pyrite (**p**) which have replaced some skeletal material. Sample from depth of 93.7 m in JMBS-11. Plane polarized light. (Scale bar = 100 μm).

A
m
B
c
m
C
D

PLATE 22

(A) Polished slab of a type III hardground from the upper part of member D of the Fort Simpson Formation. Note that the quartzose wackestone matrix of the hardground (**h**) is mineralized by dark, finely crystalline pyrite. The material overlying the hardground is less fossiliferous. Large bored hiatus concretions occur in the material overlying the hardground. *Trypanites weisei* penetrate the concretions at a variety of angles and are made conspicuous by the concentration of pyrite around the borings. A small *Alveolites* sp. (**A**) encrusts the upper surface of a concretion. Sample from 1.1 m above the base of section HR-101. (Scale bar = 5 mm).

(B) Polished slab of a bored hiatus concretion associated with the type III hardground in member D of the Fort Simpson Formation. Note the density and various angles of the *Trypanites weisei* and the dark pyrite in the material surrounding them. Sample from 1.1 m above the base of section HR-101. (Scale bar = 5 mm).

(C) Hand sample of a hiatus concretion associated with the type II hardground form member D of the Fort Simpson Formation. Small circular openings of *Trypanites weisei* (**arrows**) occur at the outer surface of the concretion. Sample from 1.1 m above the base of section HR-101. (Scale bar = 1 cm).

(D) Hand sample of a hiatus concretions (**hc**) associated with the type III hardground in member D. Highly abraded fossil fragments (**s**) occur in close association with the concretions. Sample from 1.1 m above the base of section HR-101. (Scale bar = 1 cm).

(E) Polished core of hiatus concretions from a limestone bed in member B of the Fort Simpson Formation. Note the density and variable angles of penetration of the *Trypanites weisei* (**b**) and the pyritized microcrystalline calcite around the borings. At least two generations of pyrite rim are present (**small arrows at right**). Sample from depth of 118.8 m in HW-79-5. (Scale bar = 5 mm).

A
B
C
D
hc
b

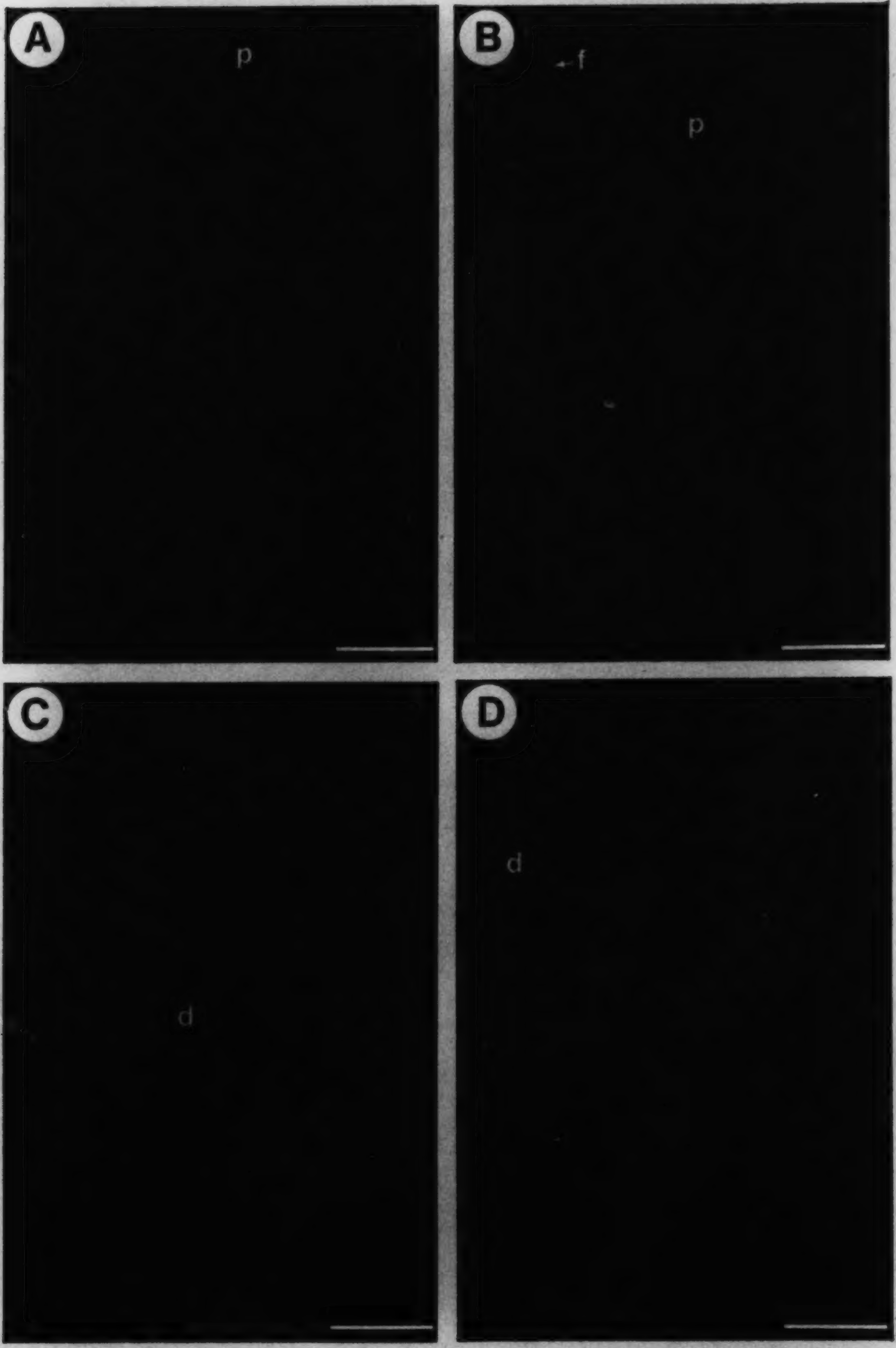
PLATE 23

(A) Cathodoluminescent microphotograph of spar calcite filled *Trypanites weisei* from the type II hardground in Plate 17. The boring (**b**) is filled (compare to plane polarized view in Plate 21A) by orange luminescent spar (**s**) and bright, distinctly zoned, orange luminescent spar (**zs**). The calcite spar is overlain by nondescript, dull orange luminescent micrite (**m**). Note the occurrence of opaque pyrite (**p**) at the contact between the spar and micrite. The matrix of the hardground displays a homogeneous, dull orange luminescence. (Scale bar = 500 μm).

(B) Cathodoluminescent microphotograph of *Trypanites weisei* from the type II hardground in Plate 17. Pyrite (**p**) occurs at the upper surface of the hardground. Notice that the hardground and the fill of the boring have been penetrated by a fracture containing non-luminescent to dull red luminescent calcite. The fracture cuts the relatively late stage pyrite but does not penetrate the material overlying the hardground. The micrite filling the boring is more brightly luminescent than that of the matrix of the hardground. (Scale bar = 500 μm).

(C) Cathodoluminescent microphotograph of a calcite spar filled brachiopod (**br**) from a type I hardground from the top of member A of the Fort Simpson Formation. Note the presence of at least four generations of calcite cement (**a to d**). Dull orange luminescent micrite (**a**) lines the interior of the shell and is overlain by distinctly zoned, bright orange luminescent columnar calcite (**b**). A third generation of cement consists of larger, blocky, dull orange luminescent calcite crystals (**c**). The central portion of the cavity was occluded by a late, blocky, non-luminescent calcite (**d**). Sample from a depth of 189.1 m in HW-79-3. (Scale bar = 500 μm).

(D) Cathodoluminescent microphotograph of the same sample as (C), but different view. Note the three different generations of calcite cement (**b, c, d**). The cements and the brachiopod are cross cut by a late fracture filled by non-luminescent to dull red luminescent calcite. Sample from a depth of 189.1 m in HW-79-3. (Scale bar = 500 μm).


A
p
B
f
p
C
d
D
d

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